Memoirs of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE.
VOL. XLVII. No. 1.

SEASONAL DEPOSITION IN AQUEO-GLACIAL SEDIMENTS.

BY
ROBERT W. SAYLES.

WITH SIXTEEN PLATES.

CAMBRIDGE, U. S. A.:
Printed for the Museum.
FEBRUARY, 1919.

CONTENTS.

SEASONAL DEPOSITION IN AQUEO-GLACIAL SEDIMENTS.

1. INTRODUCTION

ALTERNATIONS between coarse and fine sediments in a regular rhythmical banding have been noted by geologists for many years. To the different types of banding, various causes have been ascribed. That seasonal variation in deposition does not account for all kinds of banding is perfectly clear. In this paper only the banding in clay sediments associated with glacial deposits will be discussed. It is suspected that the banding in many slates, without associated glacial deposits, may be due to variations in seasonal deposition, but until the banded glacial sediments have been thoroughly studied, and the criteria fully determined, it is inadvisable to discuss these other well-banded sedimentary rocks.

I wish to acknowledge my appreciation of the helpful advice and encouragement given me in this work by my colleagues, Profs. W. W. Atwood, J. B. Woodworth, and E. C. Jeffrey. Professor Atwood carefully examined the slate at Squantum with me in November, 1915, and also visited the section of the clays at Woodsville, N. H. Professor Woodworth very kindly read my manuscript and gave invaluable criticism. To Professor Jeffrey I am much indebted for the photomicrographs, Plate 16. Mr. Frank B. Taylor spent two days with me on the Squantum tillite and slate formations, and favored me with his opinion on the problem of seasonal banding in the slate at Squantum.

2. LITERATURE ON SEASONAL BANDING IN GLACIAL CLAYS

For many years geologists have noted the strikingly even lamination of glacial clays. Some observers have attributed such regularity to seasonal deposition, but only recently have geologists felt confident that this regularly alternating deposition of coarse and fine sediment could be used as a means of recording past time.

The first mention that has come to my notice, of the idea that these regular layers might mean years, was made by Edward Hitchcock in 1841. He wrote:

> "The layers of our diluvial clay rarely exceed half an inch in thickness in the valley of the Connecticut. In each layer the coarsest part of the materials is invariably placed at the bottom; and there is a gradual diminution of fineness upward, until at the top it is exceedingly fine clay. This arrangement is just as we might expect from deposition in water; and it shows perfectly quiet water. Probably each layer marks the annual deposit; or the result of a freshet." E. HITCHCOCK, 1841, 2, p. 359, 360.

These words were written just before Hitchcock accepted the theory of the Glacial period as expounded by Agassiz and Charpentier in 1835. It is sufficient to realize that the regular layers were considered at an early date.

In Europe, during 1878 de Geer noted the regular banding in the glacial clays of Sweden and attributed their regularity to annual or seasonal deposition. To de Geer more than to anyone else we owe the firm foundation on which the theory of seasonal or annual deposition in these glacial clays rests. He was the first geologist to explain the origin of the banding and also the first to prove the truth of his theory. For many years he worked toward the solution of the problem and he gave a preliminary account in a lecture before the Geological Society of Stockholm in 1884. Not until 1912, however, did he publish his results in detail.

At the International Congress of Geologists at Stockholm in 1910 de Geer read an impressive paper, A geochronology of the last 12,000 years (de Geer, 1912), a paper so important that I quote significant parts of it here:

> "Geology is the history of the earth, but hitherto it has been a history without years. It is true that many attempts have been made to obtain time-computations for certain parts of that history, but none of them has been capable to stand a closer trial. Thus, the very able authors [Chamberlin & Salisbury] of one of our lately published textbooks of geology say (1): 'The desire to measure the great events of geological history in terms of years increases as events approach our own period and more intimately affect human affairs. The difficulties attending such attempts are, however, formidable, and the results have an uncertain value. At best they do little more than indicate the order of magnitude of the periods involved. Geological processes are very complex, and each of the co-operating factors is subject to variations, and such a combination of uncertain variables introduces a wide range of uncertainty into the results.'
>
> "Under such circumstances it may be suitable here to place briefly before you a new, exact method of investigation, through which it is possible, by actual counting of annual layers, to establish a real geochronology, for a period reaching from our time backwards some 12,000 years.
>
> "As a basis for this chronology have been used certain late glacial and postglacial, periodically laminated sediments in which the deposition for every single year can be discriminated. By actual countings and successive combinations of a great number of sections

with regular intervals along a line extending from the southernmost to the central part of Sweden it has been possible not only to sum up the whole series of centuries it has taken for the ice-border to retire this distance, or some 800 km, but also to estimate the length of the postglacial epoch after the disappearance of the ice and up to our days.

"Of the late glacial sediments the most important is a glaci-marine clay, the "*varvig lera*" (hvarfvig lera), so called from its "*varves*" (2) or its periodical laminæ of different colour and grain.

"Already at my first field-work as a geologist, in 1878, I was struck by the regularity of these laminæ, much reminding of the annual rings of the trees. The next year, therefore I commenced, and during the following years pursued, detailed investigations and measurements of these laminæ in different parts of Sweden. The laminæ were found to be so regular and so continuous that they could scarcely be due to any less regular period than the annual one. I therefore ventured in 1882 to advance the view that there might be a close connection between the periodical laminæ of the clay and the annual ablation of the land-ice (3). Two years afterwards the investigations had proceeded so far that, being confirmed in my opinion that the laminæ were really annual, and having found out a way for correlating annual layers at different places by means of diagrams, I could, in a lecture read before our Geological Society in Stockholm, indicate the way by which a real chronology for the last part of the Ice-age could be obtained (4). A few months afterwards I also succeeded in finding the first correlation between the clay-layers at three points, though not very far from one another. In 1889 I found — and mapped — in the neighborhood, NW of Stockholm, a thereto [hitherto] overlooked kind of certainly quite small, but very characteristic terminal moraines, which proved to be periodically arranged in rows with somewhat regular intervals of about 200–300 m. This led me to point out the possibility that these ridges might correspond to the stop in the recession of the ice-border, which was probably caused by each winter, and that this might be ascertained by investigation of the successive annual clay-layers between some neighbouring ridges (5). This kind of moraines has since that time been found to be quite common in the lower parts of the land, and at first I had therefore the intention of pursuing the chronological investigations by means of a careful mapping of the annual moraines.

* * * * *

"By detailed studies of some oses, especially at Stockholm and Uppsala, and, later on, also at Dal's Ed it had turned out that also the oses are of a pronounced periodical structure, marked by centres of coarser material, on their southern side gradually passing into finer gravel and sand. This led me to a new explanation of their formation as successive submarginal delta-deposits, formed in the glacier-arches of the receding land-ice, and probably corresponding to the annual "*varves*" of the finest, clayey sediment and to the annual moraines (6).

"Finally, in 1904, I happened to get a very good correlation between two clay-sections 1 km apart from each other, and now I determined to make an earnest attempt to realize my old plan for a clay-chronology.

"By investigating some forty points in the Stockholm region it was soon found that the clay-correlation offered less difficulty than thereto suspected and was — the localities of observation being well chosen — as a rule performable at distances of 1 km. This being ascertained, I secured the assistance of a number of students from the universities of Stockholm and Uppsala, ten from each, and after some training they went all out on a summer morning in 1905, each of them to his special part of a line about 200 km. long, running, as seen from the map Pl. 1, past Stockholm and Uppsala through the Södermanland-Uppland peninsula, from the great Fennoskandian moraines at its southern end to the river Dalälfven to

the north, and going as nearly as possible in the direction of the ice-recession. The main work was performed in four days; though the filling up of some lacunæ at difficult points could be performed only after several repeated attempts.

"Among the different results it may suffice here to mention, that I now finally got the conclusive proofs for the assumption that the individual "*varves*" had a very wide distribution. Thus it was shown that it often exceeded some fifty km, and that the cubic-mass of the "varves" must be measured by millions of m^3. This together with their regular structure definitively showed, that they could not be due to any local or accidental cause of smaller importance or less pronounced periodicity than the climatic period of the year. On the other hand, it seems equally impossible that every sharply marked *varve* should correspond to any hypothetical and, in every case, indistinctly limited series of years without showing any registration of the in fact so sharply accentuated period of the single year. Indeed, it seems to me quite as improbable that the melting-season of the land-ice should not put its stamp upon the annual sedimentation, as that this should not be the case with the annual period of vegetation in relation to the annual rings of the trees.

"In the following year, with the assistance of partly the same staff of co-operators, the investigation was extended to the rest of the line 800 km in length between Skåne (Scania) and that point of the late-glacial ice-shed — in S. Jämtland — where the last ice-remnant first became divided into two parts. Also this campaign was successful, though at several places lacunæ had to be left for the moment.

"However, the main thing was that the plan had been found to be quite performable even under such highly varying conditions as had been met with along this extended line, and that it now evidently was only a question of labour and patience, gradually to work out the chronological and climatical record almost as far into detail as might be wished.

"In my later completion and correlation work it was a great pleasure to me to find how able and enthusiastic in their work my numerous young collaborators had been, and how good and reliable were their results. Never lacunae were left, where the difficulties had not really been too serious for the time available.

"The natural conditions upon which the plan for the whole investigation was founded are the following. When the late-glacial land-ice receded from Sweden, the lower parts of the land were still depressed below the surface of the sea, and during the warm season of every year the melting-water from the surface of the great land-ice sank down through its crevasses and found its way along the bottom of the ice, where it was pushed forward under strong hydrostatic pressure, thereby sweeping away considerable masses of moraine-matter which were transformed into water-worn sediment. Where these overburdened rivers, at the steep border of the land-ice, reached the stagnant water of the sea, the subglacial river-tunnels widened rapidly into glacier-arches, and at the same time the rapidity and transporting power of the water slackened, thus causing a deposition of the great cobbles and the coarsest material at the innermost, proximal part of the arch, while, further out, smaller pebbles and gravel and ultimately almost only sand was deposited at the more distal part of such a submarginal delta in the very mouth of the arch. Still farther out in the sea off the ice-border the sand becomes thinner, finer, and more and more interstratified with clay-layers, which ultimately become dominant and free from sand.

"Thus every ose-centre is nothing else than the proximal glacier-arch portion of an annual layer and, if this be compared to a fan, corresponds to the very handle of it.

"Every year, by the melting during the warm season, followed also a recession of the steep ice-edge with the glacier-arch and its river-mouth. This retreat, on the whole quite dominating, was during winter-time somewhat counter-acted by a slight advance, at many places wonderfully well registered by the small, but well-marked winter-moraines.

"Every following mild season caused a new recession and a formation of a new fan of gravel, sand, and clay. Thus the whole series of those fans are placed as tiles, one over another, the uppermost always having their northern, or proximal border extending so much over that of the underlying as the ice-border had receded and the sea extended since the last year. As the recession was often very regular, the handles of the fans were gradually combined to ridges, thereby giving rise to the oses, the periodical structure of which has been afterwards often more or less concealed by the smoothening wave-action during the later land-emergence.

"From this cause and owing to the thickness and coarseness of the material together with the casualities in its deposition the most proximal parts of the annual layers are as a rule not well adapted for direct chronological determinations, though, of course, a regular development of the very ose-deposits is a reliable sign that the ice-recession in such a region has been of a corresponding regularity.

"Yet, it is the fine, extraglacial, clayey sediment that affords the most valuable means for the chronological investigations." DE GEER, 1912, p. 241–245.

At this point de Geer described the method used in counting the annual layers. The description is too long to quote. He found the number of late-glacial layers to be about 5,000. He then describes the effect of wave action on the deposits and the impossibility of counting the postglacial layers of southern Sweden. Later on he described how he counted the postglacial layers:

"This lack of seasonal lamination in the postglacial clays of Southern Sweden made it impossible here to fill out the great gap between the late-glacial chronology and the historical one. But one of the most energetical and successful of my young collaborators, R. Lidén, had found a periodical, and evidently seasonal lamination in postglacial fjord-deposits along the river Ångermanälfven in Norrland and also commenced their investigation. This work during the first years meeting with great difficulties, I got the idea that the postglacial sediments in the Lake of Ragunda, which was totally drained in 1796, might perhaps afford a more favourable opportunity for the investigation of the postglacial chronology, and, therefore, in the autumn before the congress I made a visit to Ragunda, just to look if there were any chances. These were indeed found to be so great that I determined at once to stay, and, by the collaboration of my wife, I succeeded in three weeks to work out a continuous section from the morainic bottom, upon which followed about 400 beautifully laminated, late-glacial clay-layers and thereupon about 700 somewhat less sharply accentuated layers of a black-banded postglacial fjord-clay. This clay passes upwards into well marked seasonal layers of alternating fine, sandy sediment and silt, which had certainly for the most part with exception of the lowermost ones been deposited in the basin of the ancient Lake of Ragunda, since its ose-dammed outlet had been uplifted above the level of the fjord and seemingly until 1796, when the whole ose-dam was artificially cut through and the lake totally drained, thereby giving us access to such a unique section, registering probably the whole postglacial epoch." DE GEER, 1912, p. 251.

De Geer found that there were 7,000 of these postglacial layers and these added to the late-glacial layers makes 12,000 as the total number of years, approximately, since the ice left southern Scania. From his study of the ice recession in Sweden, de Geer felt justified in assuming that it took at least

5,000 years for the ice to retreat from its most southern limit in Germany to southern Scania. This would make a total of 17,000 years for the whole retreat of the great Scandinavian glacier of the last Glacial epoch from its greatest extension to the present mountain limits, *plus* the time which has elapsed since the ice reached its relatively stationary condition of today.

Many years after Hitchcock recorded his observations, Emerson, **1887**, his successor, made a study of these same banded glacial clays in the Connecticut Valley and came to the following conclusions:

> "In all its deeper waters the flat, laminated clays were being deposited, while the sands of the deltas were extending out from the shore. Each layer of the clay, on an average of two-fifths of an inch thick, represents a year's deposit. The clays are, at the Northampton bridge, above 120 feet thick, and at East Street bridge above fifty feet, which would give numbers for the duration of the lake favoring the idea that the Glacial period was not more than 10,000 years ago, one of the shortest estimates. In these clays I have found an abundant glacial flora, proving that the lake succeeded immediately to the ice, and I have found indications of several re-advances of the ice ploughing up the sands of the lake." EMERSON, 1887, p. 404, 405.

In **1898**, Emerson, explaining the laminated clays near Northampton, writes:

> "While the "fat" portions of the clay layers are very uniform in thickness and grain, the variation in the thickness of the layers depends upon a thickening or thinning of the sandy portions of these layers, which may or may not be accompanied by a corresponding change in the grain of the latter. At times the fat laminæ separate and take in between them 12 to 16 inches of a sand but little coarser than that of the coarse portion of the layers at the Hadley locality, as is the case in a large portion of the Wapping cutting. At other times the grain increases to medium or coarse.
>
> "The fat laminæ seem to be purely a sediment of matter held in suspension when there was scarcely a trace of current, the lean laminæ to contain in gradually increasing proportion the fine material carried over the bottom by the friction of a slow current, which was regularly intensified for the formation of the thin films of sand which separate the layers. One finds these clays as regular as a pile of thin deals over all the basin, and I imagine that each layer represents a year's work of the flooded river. The fat layers were thrown down in the winter impartially over every portion of the lake bottom, and with the breaking up of the ice in spring the flood swept it off those portions where it had strong current, at times just crumpling it, as shown in figs. 39 and 40, p. 647, but over the deep lake bottom only rippling its surface, the fat tenacious clay resisting erosion slightly, while the coarse material brought in by the tributaries was pushed in sheets out over the delta flats and dumped over their fronts, and in small quantity carried out over the clays. In exceptional floods thin films of these sands were carried down across the very middle of the lake, as at the Hadley locality, and came at the beginning of the spring, for the coarse sand rests directly in rippled hollows of the surface of the finest clay. In this sand are found the twigs and reeds and leaves brought down by the tributaries, and the sands grade upward into the lean portion of the layer, which represents the uniform high water of the glacial river during the summer and which is a true "gletchermilch" and this in its turn grades upward into the fat deposits produced by the clarifying of the waters during the succeeding winter. This would conspire with the fact

that the mass of the coarse material of these deposits has been brought in from the sides and moved but little downstream, to indicate a low pitch for the valley during the time of the glacial stream. * * *

"The considerations of the preceding section afford data for a calculation of the time occupied by the deposition of the clays, which is presented as interesting rather than specially valuable. If we take the clays exposed in the south of the Camp Meeting cutting and in the river bank adjacent, a thickness of 72 feet is exposed down to the water level, which would give, at an average of two-fifths of an inch per layer, 2,155 years. If we take the boring at the Northampton bridge, 113 feet, we have 3,390 years. As these two neighboring sections are measured, the one up and the other down, from the river level, we may add these two numbers to obtain a maximum time for the deposition of the clays — 5,545 years." EMERSON, 1898, p. 706, 707.

A few years, **1894**, after Emerson's first (1887) description of his theory of seasonal deposition in glacial clays, Taylor without knowledge of the work of de Geer and Emerson came to similar conclusions. Concerning the glacial clays and silts at Bracebridge, Ontario, Taylor wrote:

"Take, for example, the silt beds at Bracebridge. The whole set of phenomena at this place is extremely instructive. The laminations of clay and silt are associated in pairs which are almost without exception about half an inch in thickness. On weathered surfaces the principal part of each layer is a greenish gray clay, and this is separated from the next layer of clay in each case by a layer of white silt, an eighth to a sixteenth of an inch in thickness. There are some variations in the composition of the deposit at each locality, but they are confined chiefly to varying proportions of the two materials. In a few places I found the clay almost absent and the silt layer thicker than usual. In other places the variation was reverse of this. It seems plain enough that the silt and the clay must represent two slightly different conditions of sedimentation; and the orderly way in which the layers alternate shows that a layer of silt and a layer of clay taken together constitute one complete round of change. This points to recurrence and almost certainly to periodicity. Tides, storms, and the annual round of the seasons, are the only recurrent variations liable to affect sedimentation. Of these the tides and the seasons are periodic, but storms are irregular. Neither tides nor storms afford a satisfactory explanation. For the one is much too short in its period, and the other too irregular. It seems impossible that the pairs of layers can represent anything but annual periods of deposition, and if this be the case several important conclusions follow. Considering the great thickness of the whole deposit, the length of time which must be allowed for its formation can hardly be less than several thousand years. Indeed, if we suppose the laminations to be uniform, and the maximum depth of the whole original deposit to have been 100 feet, the time of deposition would be about 2,500 years. And this, it should be noted, would be not the whole time of the submergence, but only the time during which the conditions of still-water sedimentation existed at that level, not counting the two periods unfavorable to this kind of sedimentation, one as the water was rising and the other as it was receding, during both of which shallow water conditions prevailed." TAYLOR, 1894, p. 288, 289.

In **1902** Coleman, describing the laminated clays of the Don River interglacial beds, wrote:

"The peaty clays often show fine lamination with thin silty layers at intervals of 1½ or 2 inches, the latter often charged with spruce needles, beetles' wings, etc. These

peaty layers are not always distinct, and there are beds of the clay 2 or 3 feet thick which do not show them, the peaty and silty matter being more or less mixed with the clay in these parts. It is natural to assume that the silty layers are of an annual character, and if we reckon that two inches of clay were deposited annually over the delta, which was 18½ inches wide, the 94 feet required 564 years to form.

How long the 55 feet of overlying stratified sand needed for their formation is hard to guess, but half a foot a year seems as rapid a rate of deposit as one can assume for so wide a delta. This would give 110 years for the interglacial sands." COLEMAN, 1902, p. 73.

Coleman found other evidence to prove that these Don beds did not give the whole record of the Interglacial period. It is enough to record his opinion of the banded clays.

In 1905 Berkey published a detailed account of the laminated interglacial clays of Grantsburg, Wisconsin. I quote his description of the characters of these clays and some of his chronological deductions:

"These clays are all strongly laminated. The laminæ vary in thickness from a mere film to several inches in different parts of the deposit, but are comparatively uniform in any particular zone. Their average thickness in the upper part of the deposit is about a quarter of an inch. The average thickness nearer the middle is about one-tenth of an inch. Less uniformity is observable near the top than in any other zone.

"The lamination is extremely regular and approximately horizontal. Small crumplings or bunchings occur, but are rare.

"The general color is red from top to bottom. On closer inspection, however, the laminæ are seen to be of two types — a deep red one, and a gray, which alternate without exception throughout the deposit.

"Very perfect water-sorting is evident from a study of these individual laminæ. The gray ones are comparatively coarse-grained, containing maximum diameter of 0.06 mm. Diameters of 0.02 to 0.03 mm are very common, while of course there is much finer matter. The red laminæ are composed of extremely fine grains and flakes. There are no grains at all comparable to the sizes given above. Average diameters are less than 0.002 mm.

"The passage from one type to the other is sometimes gradual and sometimes abrupt. As a rule, the gradual changes hold for all cases in passing upward from a gray to a red lamina. The abrupt changes are noted in passage upward from a red to a gray one. Evidently there is some sort of unity between each gray lamina and the overlying red one throughout the series.

"Taking, therefore, the double lamina — *i. e.*, a gray and the succeeding red one above — as a unit, the following facts obtain: The most irregular lines in the lamination are at the very base of the gray laminæ. There are sinuosities on a small scale that simulate erosion unconformities. The coarsest grains seen anywhere in the material are in these small embayments along this line. There is an occasional streakiness of the gray laminæ with the finer red material, but not uniformly developed. The change to red, in rising from the base of the gray lamina, takes place very gradually and gives a much more even line or band than that at the base. The change to red color is no more marked than the change to finer and finer grain. There is no streakiness in the red layers." BERKEY, 1905, p. 36, 37.

Further on in this same paper (*loc. cit.*, p. 40, 41) Berkey says:

"The laminated clays are no doubt a lake deposit. The uniform succession of laminæ, the relationship between the red and gray, and the constancy of their characters lead one to look for some uniformly periodic cause of formation.

"The presence of comparatively large grains throughout the gray laminæ shows a continuance of supply of new material during its accumulation at least, while the presence of some streakiness of finer red matter occasionally in them indicates fluctuations or lulls within this period of supply.

"The absence of all large fragments in the red laminæ, their uniformity of succession, and their gradual increase in fineness of grain seem to argue a period of complete cessation of supply from without and complete protection from disturbances.

"This periodic supply, then, must mark either successive storms or successive thawings of neighboring glacial ice. If the latter, then the period is seasonal, and each unit of lamination, a gray and a succeeding red layer together, represents a year of time. On this supposition, the summer thawings of the glaciers furnished silt to the lake then covering the Grantsburg area, and left behind great quantities of coarser materials to be later spread as the poorest of northern soils. Winters checked the supply, coated the lake with ice, and in this quiet season the finest sediment settled down in the uniform red laminæ of the clay deposit.

"The deposits themselves have further evidence on this point. It is scarcely conceivable that a supply controlled by spasmodic periods, such as storms, could produce uniformity either in thickness or in distribution. Variations would be expected to be notable and frequent, and at random with occasional breaks of a much more pronounced character. On the contrary, at any given horizon the thicknesses are comparatively uniform and there are no breaks of a higher order than those of the single unit. If, furthermore, the succeeding laminæ represent seasonal supply from a more or less proximate ice margin, succeeding seasons might be expected to give fairly equivalent results, greatest uniformity being developed when the ice margin is distant, and greatest variation when the ice is nearest. Other things being equal, when the supply is near by, a greater quantity of matter would reach the lake in a given season, and in connection with the general tendency or character of the season there ought to be more irregularity and greater thickness of deposit. In terms of the clays themselves, the laminæ of the middle zone should be most uniform and of least average thickness, while those of the top and bottom zones should be most variable. This is easily seen to be true in the deposit. The greatest irregularities are near the top. With a retreat of the ice margin to near its maximum withdrawal the middle zone of laminæ must have been laid down. A seasonal interpretation accords well with the facts. Even the streakiness seen in the thicker gray layers makes room for storms or other fluctuations within the season itself, and supports the other interpretation for the more uniform breaks.

"If the seasonal interpretation may be regarded as established, it remains only to compute the number of units of deposition in order to estimate the number of years the deposit was in accumulating. This done, we need but to connect this episode in the general ice-retreat with its proper limitations in order to get the force of its bearing upon postglacial history."

In Iceland, Ferguson, 1906, mentions annual layers in the glacial deposits associated with igneous materials. There he found alternating clays and sandy layers. I quote:

"The second moraine, at the point shown in the section, is almost hidden by the talus. A few feet above the moraine is a small outcrop of a much contorted tufaceous sandstone. This contortion seems inexplicable, except through the action of an advancing glacier, thus showing, with the earlier advance supplied by the ground moraine below it, a twofold advance and retreat of the ice during the period represented by this sedimentary series.

"Above the contorted tufaceous sandstone is almost 100 feet of flat-lying ripple-marked

sandstone, alternating between layers of fine clay and sandstone, the latter often spotted with pebbles of vesicular basalt. The clay layers were generally about an inch in thickness, while the sandy layers were often a foot thick and seemed to represent the annual flood of the stream. The ripple marks, by the steeper slope of the ripple ridges, showed a southwesterly direction of flow. In one place the sandstone was cut by a basalt dike which probably served as a feeder to some of the upper lava flows." FERGUSON, 1906, p. 126, 127.

Those who have tried to explain the tillite at Squantum as of igneous origin should consult Ferguson's paper. The mixture of volcanic and glacial deposits would puzzle anyone if these beds were consolidated. There is a very much greater mixture of volcanic and glacial beds in the Iceland deposits than in the rocks of the Boston basin.

In **1913** Wilson (p. 104) described banded glacial clays in Quebec and considered them to be due to seasonal deposition.

In discussing the age of the Don River glacial deposits, Wright **1914**, states:

"A clue to the length of time during which Lake Warren continued to cover the bordering land on the south side of Lake Erie is furnished by deposits recently uncovered by excavations at Fremont, Ohio. The sedimentary plain on which the city of Fremont is built lies below the 100-foot level of the lowest shoreline of Lake Warren. The sedimentary deposits consist of the material brought into Lake Erie by Sandusky River, which is spread out as a delta. The depth of these lacustrine beds is at least 25 feet. The thickness of the laminæ, according to my measurements made in several excavations, is on an average one-seventh of an inch, making 84 to the foot, making a total of 2,100, which would be the number of years required for the accumulation on the supposition that each lamina represented an annual deposit. Whatever be the date, therefore, which we assign to the upper beach of Lake Warren, that of the Iroquois beach around Lake Ontario must be 2,000 years less. This, according to my calculation, would bring the date of the 200-foot shelf at Toronto at about 10,000 years." WRIGHT, 1914, p. 208, 209.

3. BANDED CLAYS IN THE CONNECTICUT VALLEY AND IN RHODE ISLAND

In New England, the best exposures of banded glacial clays are in the Connecticut Valley. Emerson has studied the Massachusetts localities and described them in detail. During the summer of 1916, I examined the clays along both sides of the Connecticut River from Hanover, N. H., as far north as McIndoes, Vt., a distance of forty miles. In all the exposures seen, regular banding was found. The types of the banding varied. In some cases the thickness of the coarse component of the deposit was about equal to the fine component. In other cases the coarse was thicker than the fine. In the thin deposits of finest material the fine layer was found thicker as a rule than the coarse layer, although the opposite of this condition was found. From a comparison of the various deposits seen it is natural to assume that the extremely regular alternations of fine and coarse materials, as displayed in the banding, mean the differences in the conditions of deposition corresponding to winter and summer. Various disturbing factors have at times intruded themselves in such a way as to make interruptions or breaks in the regular order. Only in deep or quiet water can deposition go on undisturbed. In proof of this it may be said that the coarser banded materials invariably show the greatest irregularities, and that the finest clays show the most regular intervals in banding, and the least evidence of disturbing factors.

In examining the clays on both sides of the Connecticut River many exposures were visited. To describe all the exposures would be unnecessary. It will be sufficient for the purposes of this inquiry to choose a few of the well-exposed localities and give a full account of my field observations, with short statements of important findings in a few other localities in the Connecticut and Ammonoosuc Valleys.

Goldthwait gave me verbal directions to a locality on the Vermont side of the Connecticut River about two miles north of Hanover, N. H. I spent a part of one day at this locality and the following description is based on the observations made. About thirty feet above the river it was seen that sand rested on the underlying till. No gravel was observed here. The sand was of coarse and fine texture with no marked regularity of interval between the layers. These irregularly stratified sands continued with gradually increasing fineness of grain, up to a level about twenty-five feet above the till, where a layer of clay

was discovered about six inches thick. This was followed by a sandy-silt layer three feet thick and then another layer of clay not quite as thick as the first clay layer. (See Plate 4, fig. 1). The alternating layers of clay and sand continued upward for about twenty-five feet with a most remarkable and regular diminution in the thickness of both the fine and coarse components. At the top of this deposit of regularly banded clays the combination of a fine and coarse component did not measure more than three fourths of an inch. On account of the abrupt ending of the layers at this point, at the level of the surface of one of the river terraces, there is no doubt but that a great many of the banded layers have been eroded in the cutting of the terrace. (See Plate 5, fig. 1). In a case like this there can be very little doubt but that the regular thinning of the layers was due to a recession of the ice front. The retreat was rapid. The thicknesses of the coarse or summer components are always much greater than the fine or winter components. This would indicate that interglacial conditions were possibly in force at this time and place. I observed no contorted zones due to grounding bergs, so it is evident that the main path of drifting bergs was not at this place. The sediments also from the bottom to the top of this deposit indicate very slowly moving currents and not such as would be found in the main current of the lake.

About seven miles south of Wells River and a mile north of Newbury, Vermont, there is an exposure of well-banded clay and very fine sand. The thinnest layers are at the bottom and the stratification grows thicker upward. The regularity of interval is very marked. The coarse components are slightly thicker than the fine. About fifteen feet only of the material can be seen. At the bottom the two components average about two and one half inches, an inch for the fine and an inch and a half for the coarse. Near the top of the section the yearly deposit averages about four inches and about three feet below the top there are irregular strata of sand and gravel with no definite seasonal bands. The change from thin to thick components in the deposits at this place with the irregular coarse material at the top would indicate advancing ice. That the fine and coarse layers are almost of the same thickness would also indicate cold conditions. The melting of large glaciers in a warm period should yield a large summer deposit and a small winter deposit, as exemplified in the banded clays near Hanover, described above. No till was found above these banded deposits, and no contorted zones were observed. It is probable that the ice did not at this time reach so far south as this locality and was simply a local advance of short duration.

At Wells River there are exposures of well-banded clays which deserve more careful study than I have given them. About 150 feet west of the toll-bridge which connects Wells River and Woodsville, there is an interesting exposure of banded clays on the west side of the highway. The banding is extremely regular at the level of the road and upward for ten feet. The two components of the banding average about an inch in thickness, one half an inch for each component. A change in the summer components may be noted about twelve feet above the road. The material changes from rock-flour to sand. From this point upward the sandy components increase in thickness and in coarse texture, and about three feet from the top irregular sand and coarse gravel layers appear. Contortions may be seen in parts of the deposit. On the left all the layers appear to have been pushed, and the direction of the force was from west to east.

About 100 yards to the N. W. on the level of the upper surface of the exposure just described, is the Wells River railway station. To the north of the station across the tracks is a high bank of banded clay showing a huge contorted zone, fifteen to twenty feet thick. It is evident that advancing ice produced the results observed here. The clays merge into sand near the top of the deposit. From a study of the contortions I believe that the ice tongue which caused them came from the northwest, and may not have been more than a temporary oscillation. The contortions die out towards the east. The lower deposit, first described, and this upper deposit opposite the railway station, were continuous with each other at one time. The coarse sands and gravels capping the lower deposit gave evidence of approaching ice. Above this horizon clays were deposited giving evidence of receding ice. The ice then advanced again, during this later phase of deposition, and contorted not only the upper deposit of clays, but also the lower deposit. The deposits filled the valley at one time and the present terraced condition of the valley is due to subsequent river cutting. It is possible that the water from the same ice which contorted these clays was responsible for the banded deposits near Newbury (p. 16), and that the ice itself did not then reach Newbury. A further study of this interesting locality is desirable. As the main purpose of this paper is to compare Pleistocene with Permian extraglacial sediments it will not be necessary to follow out the history of these banded clays here. In a future paper I hope to present an account of the sequence of events near Wells River.

At Woodsville, about 300 yards northeast of the covered bridge which

crosses the Ammonoosuc River, is the brick-yard and clay-pit of E. M. Lamarre. The bottom of the clay at its contact with the underlying till is, by aneroid, twenty-eight feet above the Connecticut River. The actual contact is not, at present, visible, but till outcrops about 100 feet to the north, and the present bottom of the clay-pit is estimated to be about seven feet above the top of this till horizon. There are so many characters in this Woodsville locality which resemble those found in the slate at Squantum that a careful description will be given.

As remarked above, there are about seven feet of clay under the present bottom of the lowest part of the pit. The first layers visible at the bottom average one fourth of an inch in thickness and this width of the annual deposits among the first few feet is repeated with an extremely even interval. This first group of bands is four feet six inches thick (Fig. 1, 1, no. 1).[1] Near the top, the layers increase to one half inch in thickness. At this point there appears a layer of rock-flour mixed with pebbles which resembles till. This material appears to have dropped from floating ice, whether ice of an advancing glacier or of a large berg it is not possible to say. The thickening annual deposits just below might indicate an advancing glacier. The lack of contortions in this till layer and in the lower deposits and the even upper surface of the till layer prove that the water at this point was deep enough to float the ice above it. On the till deposit is a layer of rock-flour ten inches thick (No. 2). This would appear to indicate a retreat of the glacier and that when this rock-flour was deposited, the glacial stream was not far off, for without a near supply of material, such a thick deposit of the rock-flour could not have been laid down, in what appears to be a single year. Above the rock-flour come six inches of annual deposits averaging one half inch each (No. 4). Above these again appears a deposit of rock-flour (No. 5) nine inches thick. Either the glacier advanced again or the glacial stream shifted so as to bring once more a thicker deposit. That stream action was the agent in the deposition of this rock-flour deposit is indicated by a gravel layer two inches thick (No. 6) resting on the rock-flour. This gravel is composed of well-sorted pebbles which have been scarcely water worn at all. They are mostly angular fragments of small size, very few being over one fourth of an inch in diameter. Annual deposits rest on this gravel layer to a thickness of fourteen inches (No. 7) with thicknesses averaging three fourths of an inch each. Such thick annual deposits, of such very fine material, three times as thick as the lowest ones below, might indicate

[1] See also Plate 1.

Figure 1, 1.— Section at Woodsville in the clay-pit of E. M. Lamarre.

30 About a foot of sandy clay on top of all with no evident stratification. Probably washed material from erosion.
29 Annual layers rapidly growing finer and averaging not over $\frac{1}{8}$ inch thick.
28 Annual layers with sand and clay about $\frac{1}{2}$ inch.
27 Annual layers 2 inches to $\frac{1}{2}$ inch thick.
26 Annual layers $\frac{1}{8}$ inch thick greatly contorted with rare glaciated pebbles on top.
25 Annual layers $\frac{1}{2}$ inch to $\frac{1}{4}$ inch thick.
24 Contorted layers $\frac{1}{3}$ inch thick.
23 Annual layers $\frac{1}{2}$ inch thick.

Numbers 23–29 were taken 100 feet north of 1–22.

22 Annual layers $\frac{1}{2}$ inch at bottom, $\frac{1}{4}$ at top.
21 Contortions with till.
20 Annual layers $\frac{1}{2}$ inch thick.
19 Contorted layers with trace of till.
18 Annual layers $\frac{1}{2}$ inch thick.
17 Contorted layers with till.
16 Annual layers $\frac{1}{2}$ inch thick.
15 Contorted layers with till on top.
14 Annual layers $\frac{1}{2}$ inch thick.
13 Contorted layers with till on top.
12 Annual layers $\frac{1}{2}$ inch thick.
11 Contorted layers with till on top.
10 Annual layers $\frac{1}{2}$ inch thick.
9 Till layer on (8).
8 Contorted layers with till on top.
7 Annual layers $\frac{3}{4}$ inch thick.
6 Gravel layer.
5 Rock-flour.
4 Annual layers $\frac{1}{2}$ inch thick.
3 Rock-flour.
2 Gravel and rock-flour.
1 Annual layers $\frac{1}{4}$ inch thick.

Figure 1, 2.— Section in the slate at Squantum Head, 47 feet of banded slate showing the contortions due to icebergs grounding. Section beginning 22 inches under contorted zone shown in Plate 2.

40 Contortions with pebbles.
39 Banded slate.
38 Contortions.
37 Banded slate.
36 Contortions with pebbles.
35 Banded slate.
34 Contortions with pebbles.
33 Banded slate.
32 Contortions.
31 Banded slate.
30 Contortions.
29 Banded slate.
28 Contortions with pebbles.
27 Banded slate.
26 Contortions.
25 Banded slate.
24 Contortions.
23 Banded slate.
22 Contortions.
21 Banded slate.
20 Contortions.
19 Banded slate.
18 Contortions.
17 Banded slate.
16 Contortions.
15 Banded slate.
14 Contortions.
13 Banded slate.
12 Contorted banding with pebbles.
11 Banded slate.
10 Contortions.
9 Banded slate.
8 Contortions.
7 Banded slate.
6 Contorted bands.
5 Banded slate.
4 Contorted bands with pebbles.
3 Banded slate.
2 Contorted bands with pebbles.
1 Banded slate.

The double bands in this section average about $\frac{3}{4}$ of an inch. Near the top they average about $\frac{1}{2}$ inch.


30

ice not far off. A shifting of the glacial stream nearer this locality might also explain the increase in thickness. Just above these bands comes a zone of highly contorted layers two feet thick (No. 8, 9), with till-like material two inches thick on top, with some of the pebbles pressed into the contortions. The thickness of this zone of disturbance varies considerably from north to south, and there are places where the till appears to be absent. The top of the till layer is uneven and the till layer itself is extremely variable in every way. It would appear as if an iceberg of considerable size had dragged over the bottom, destroying some layers, contorting many of those below, and leaving a deposit of till on the top and here and there pressing pebbles down into the folded bands.

Above this very highly contorted zone come two feet six inches of beautifully banded clays (No. 10), with an average thickness of one half inch each. Above these again comes another contorted zone two feet thick (No. 11) with a till deposit on top similar to the contorted zone, with its till deposit described above. Next come three feet of regular banded clays (No. 12) with deposits averaging one half inch to the year.

Above these layers comes another contorted zone one foot two inches thick (No. 13) with till material and pebbles. Above this zone comes one foot three inches (No. 14) of banded clay layers averaging about one half inch. Above these a contorted zone with till one foot thick (No. 15). Then come annual deposits ten inches thick averaging one half inch each (No. 16). Above these a contorted zone four inches thick with included pebbles (No. 17). It must be noted here that in the thinner contorted zones the till is correspondingly scarce and mixed with the folds of the contortions to a greater extent. Above the thin contorted zone (No. 17) come five inches of annual deposits (No. 18), with an average of one half inch to the year. Above these comes another contorted zone six inches thick (No. 19) with very few pebbles and little till. Then come one foot three inches of annual deposits (No. 20) averaging one half inch each. Next above these layers is another contorted zone four inches thick (No. 21) with a few pebbles. Above this zone annual layers were deposited for at least 400 years without any disturbing bergs whatever (No. 22).

It will be noted in Figure 1, that the contortions are greater in the lower zones than in those which follow. It is also to be noted that the till deposits of these larger contorted zones are more marked than in the thinner zones above, that in these thinner zones the till is almost wanting, only pebbles being found, here and there, mixed with the folds. The thinner and thinner zones of con-

tortion would appear to indicate smaller and smaller icebergs, for it is evident that a large berg would create more disturbance in the layers than a small one. Progressively smaller bergs might indicate a retreating ice front. The farther away the ice the smaller the bergs would be, on account of melting. On the other hand, the depth of water would determine the size of berg which could be floated at a given place and time, thus a change in the water level might be the controlling factor. What is to decide which factor controlled the size of the bergs which contorted these layers? A study of the thicknesses and character of the annual deposits may possibly throw some light on this question. The lowest annual deposits visible in this section average one fourth of an inch in thickness. Upward, this thickness increases and just below the deposit of rock-flour and pebbles (No. 2) the thicknesses of the annual deposits average one half of an inch. In the group of bands numbered 7, the thickness reaches three fourths of an inch to each couple. Until the upper part of group (No. 22) is reached, the thicknesses of the units do not vary to any great extent, averaging one half inch, and these are one fourth inch thick. The constancy of the thicknesses of the annual deposits during this whole period of not less than 1,100 years would appear to indicate that the ice was not many miles away when the deposits were made, and that it did not at any time retreat so far as to cause the bergs to be reduced in size to the extent indicated by the decreasing thicknesses of the contorted zones. A change in the depth of the water, to shallower conditions, might be indicated by the thinning of the contorted zones. The gradual filling of the basin of deposition with deposits would, other things being equal, decrease the depth of water. If to this should be added an elevation of the land the depth of the water would be still further decreased.

Tarr, **1909**, has given a good description of the calving of bergs from the Hubbard glacier of Alaska. In connection with this subject it is appropriate to quote his own words:

"The discharge of a great many icebergs was witnessed, some of them from excellent points of observation near at hand. Far the greater number of the falls consisted of a crumbling of the crevassed ice above the water level, giving rise to ice cascades, at a distance resembling falling water. Such discharges produce very small fragments. In other cases large masses fell forward from the ice cliff, producing great commotion in the water near the glacier front.

"Occasionally masses of ice rose from beneath the water at a considerable distance from the ice front. Russell describes the latter condition and postulates a projecting ice foot extending fully a thousand feet in front of the ice cliffs. He gives a graphic description of the formation of such icebergs, which are sometimes 200 to 300 feet in diameter, and usually much larger than those falling from the face of the cliffs. Some of these large icebergs rise 40 to 50 feet above the water.

"Bergs immediately in front of the glacier are prevailingly either white, blue, or black in color. The white bergs are derived from the ice walls above the sea; the blue ones, which are often a beautiful Antwerp blue, rise from below the water; the purely black icebergs, which are by no means uncommon, rise mainly from the base of the glacier, though a few fall from the débris-covered portions of the ice front.

"In his description of Muir Glacier, Reid postulates conditions exactly the opposite of those which Russell infers; that is, instead of a projecting ice foot Reid assumes that there is a projecting ice cliff. Only a few icebergs from Muir Glacier are discolored with débris, and Reid suggests that the discolored bergs mentioned by Russell came from the débris-covered parts of the glacier.

"My observations were in harmony with those of Russell. In several instances blue ice was seen to rise from beneath the water, though none was observed to rise as far away from the ice front as Russell states. The abundance of débris-charged icebergs near Hubbard Glacier is far too great to be explained by supplies from the very small and almost stagnant débris-covered margins, or from the limited areas of medial moraine. Moreover, the blue bergs are exceedingly abundant near the glacier, and too numerous to be accounted for by melting and overturning so soon after their discharge. Furthermore, the great amount of ice which falls from above water indicates a rapid recession of that part of the cliff, far more rapid than the rate at which melting would be expected to cause the submerged part of the ice to recede.

"Three conditions favor the projection of a submerged ice foot, as follows: (1) The warmer water at the surface of the fiord, causing undercutting of the ice there; (2) the crevassed, weathered, and thereby weakened upper portion of the glacier; (3) the attack of waves, especially those generated by the iceberg falls. The combination of these conditions would tend to produce a projecting ice foot, and the facts observed indicate the presence of such a submerged foot in this region.

"The normal condition of iceberg discharge from these glaciers may be best stated by giving a description of an actual instance of the calving of large icebergs which were seen to fall from the south side of the Nunatak Glacier ice cliff. First a small piece fell from the face; then a pinnacle at the ice front rose 50 to 100 feet, reaching well above the surface of the glacier; it then slowly turned over into the fiord, sending a large fountain of water to a height of 75 or 100 feet. Immediately following this another ice mass, clear and blue, arose from beneath the water's surface, throwing it into renewed and still greater commotion, which lasted fully five minutes as the berg rocked to and fro. A great series of ring waves spread out for nearly ten minutes, causing a heavy surf on the coast to a distance of at least 1½ miles from the glacier. Prior to this fall there was almost no floating ice in front of the glacier; five minutes after the discharge of the iceberg there was a ring of very muddy water in which floated several thousand icebergs of small size and six good-sized ones, all clean and free from drift. The ring of icebergs kept spreading until it reached both shores, advancing a half mile in each direction in about twenty minutes.* * * The larger bergs, one of which was more than 100 feet long, rose at least 30 feet above the water." TARR, 1909, p. 31, 32.

What I would call the lower clay-pit has now been described. In Figure 1, I have continued this section upward with a section 100 feet to the north. It is not possible to connect the two sections with absolute accuracy but from a close study of the two deposits and by leveling, the fairly complete section of the clays at this locality is as represented in Figure 1.

Commencing with the group of annual deposits numbered (23). This

group, three feet thick, has deposits averaging one half inch each. Above these layers comes a contorted zone three feet thick with no stony material mixed with it or lying on it. The layers in this contorted zone are not over one third of an inch thick. Above this zone come annual layers one foot six inches thick (No. 25). The couples are one half inch thick at the bottom, they gradually thin down to one fourth of an inch at the top. Above this group comes a contorted zone which varies in thickness between three feet and six feet (No. 26). (See Plate 10, fig. 1.) The annual deposits, in most of this zone are not over one eighth of an inch thick. The tops of the folds have, in places, been cut off considerably. Lying on this deformed mass is rock-flour several inches thick. I found one angular rock-fragment only in this rock-flour. Above the rock-flour, alternating layers of fine sand and clay appear, averaging about two inches thick (No. 27). Inside of five feet these thick deposits thin down to not over one half inch to the annual deposit, and from this point to the top of the clay-pit the layers gradually grow thinner, until near the top, about eighteen inches below the edge of the pit, they are not over one eighth of an inch thick. The total thickness of these upper layers is about thirteen feet (No. 27, 28, and 29). The uppermost eighteen inches appear to be unstratified clay such as would wash down from the slope above the pit. These topmost seasonal layers differ from those in the lower twenty-five feet of the Woodsville deposit in the ratio of the fine and coarse components of the annual deposits which are about equal in thickness here, while lower down the ratio is two to one in favor of the fine component.

The deposits above (No. 23) need an explanation. We have seen that in the lower pit the contorted zones grow thinner upward and that ending with (No. 21) the contortions were only four inches thick. From this point upward there are no contortions visible for nine feet. Then comes the contorted zone (No. 24) with a thickness of three feet. This zone will be discussed later after (No. 26). In the layers of group (No. 25), gradual thinning is noted and then comes the large contorted zone (No. 26). From the thinning of the layers in No. 25, 26 it would appear that the glacier had retreated rather rapidly. The highly contorted zone (No. 26) would indicate something more than dragging icebergs. It would appear as if these contortions meant, perhaps, ploughing by a relatively thin glacier. It might be objected that such a glacial advance should be heralded by thicker deposits instead of such thin layers. Would it not be highly probable, however, that such thick deposits would be destroyed by the advance of the ice over them, leaving only the contorted thinner layers

of the preceding retreat which had collected lower down? On the retreat of this ice the layers should be relatively coarse, as they are in this case, and by a continuing retreat the layers should become progressively thinner, just as they actually do. As to the depth of water in the valley, during this time, the increase in the thicknesses of the coarse components of the deposits would indicate either shallower water or warmer seasons. In any event the water was probably no deeper than it had been. The great size of the contortions and the cutting off of the folds and crumplings would indicate, in the case of an iceberg, a much larger berg than those which took part in the contortions found in the lower pit. The evidence, so far observed, points to an ice advance and not to iceberg action. So far I have found no cut-off folds nor rock material in zone (No. 24). It is possible that this zone was crumpled by shearing produced by the over-riding of the ice which crumpled zone (No. 26), above it.

By a count of the annual deposits at least 2,100 years are represented in the entire thickness of fifty-eight feet of these clays. Above the last contorted zone just described there occur about 460 double deposits to the highest part of the section. It has seemed to me that these layers register a retreat of the glacier. No account has been taken of the layers destroyed by the dragging of ice over the bottom. It is probable that several hundreds were thus obliterated. In any event, from all the evidence which these deposits present, it would appear, on the seasonal hypothesis, that there was glacial ice not a great distance from this Woodsville locality, for possibly 2,500 years. The retreat was probably not so fast as the retreat of the glaciers in Alaska or of glaciers in many other parts of the world at the present time.

On account of the consolidation of some of the gravel in the layer Number 6, these clays may be older than the last Wisconsin advance. No overlying till has been found, and no fossils discovered although microscopic fragments of macerated wood are plentiful. Future discoveries may reveal the exact age of these clays. The protected position of the deposit, in the lee of a steep hillside on the north, might have made it possible for this clay body to have escaped destruction by Wisconsin ice.

Banded clays are not rare between Wells River and McIndoes on the Vermont side of the river, a distance of eight miles. Although most of these deposits were examined, no close study has been made of them. It is sufficient to say that they all show the regular banding well marked. On the eastern side of the river, above Woodsville for eight miles, as far north as Monroe, exposures of clays near the road are lacking, although in the banks of the river there are several exposures.

In the valley of the Ammonoosuc River, which joins the Connecticut at Woodsville, there are many places where laminated glacial clays may be found. At Bath, on the west side of the river, and about 200 feet above it, there are some well-banded clays. These clays are at least 150 feet above the highest part of the Woodsville clay-pit.

At the top of the hill on the main highway just south of North Bath, there is a deposit of banded clays and silts, about 150 feet above the river. The clay here has not the fine texture found at Woodsville and the silt is almost a fine sand. The regularity of interval between the layers is not as marked as at Woodsville. In places near the bottom of the exposures, the irregularity of interval is so marked that seasonal deposition might well be questioned. (See Plate 3, fig. 2). The causes of these irregularities lies probably in shifts of the current or differences in the seasons from year to year. Higher up the regularity is much more marked, the two components of the banding having thicknesses varying between three fourths of an inch and one and one half inches, until near the top of the section, where coarser sands appear, with little approach to regular banding. As stated above, the seasonal origin of some of these layers might be questioned, and this is also true of the coarser parts of the Squantum slate (p. 45). The texture of these clays and silts appears to be about the same as the coarser slates at Squantum. The clay has not that plastic quality of the very fine material at Woodsville.

At a place about a mile north of North Bath, banding in clays may be seen on the right of the road, and about twenty feet above the river. In this section there is a contorted zone one foot thick lying between horizontal, undisturbed layers. (See Plate 8, fig. 1.) Neither pebbles nor till were found in this zone of folding in the very limited exposure seen.

At Lisbon, back of the lumber yards, a terrace of clay and silt layers rises about fifty feet above the river. The banding is peculiar in showing abrupt changes in the thicknesses of the seasonal units. At the bottom of the deposit the bands are regular in interval and the thicknesses vary between one inch and ten inches. From bottom to top the thicknesses of the units vary suddenly. (See Plate 3, fig. 1). Such sudden changes in the amounts of sediment deposited annually are probably too abrupt to be explained by either advances or retreats of a glacier or by differences in the seasons. The shifting of the stream which supplied the material for each year was probably the cause of the sudden alternations in deposition. The texture of the materials is coarser than at Woodsville, and this is equally true of all other banded clay and silt deposits of

the Ammonoosuc Valley. No contorted zones were noted at this Lisbon locality.

An important generalization must be made at this point. The clays were not everywhere deposited across the valley continuously in all places. On one side of the valley fine clays may be present while on the opposite shore sands and even gravels may be found. In order to understand this difference in deposition the conditions in the valley at the time of the withdrawal of the ice from this region must be clearly understood.

It is clear that the Connecticut Valley was a lake. The waters of the lake were probably held up on the north by the retreating glacier. On account of depression in the region described and in the St. Lawrence Valley to the north, the waters from the melting ice, instead of flowing rapidly away towards the south, in a glacial torrent, as they would do under the present conditions, were ponded back against the ice front, but forced, nevertheless, to flow southward on account of the lack of an outlet to the country under the ice to the north. Even as far south as Northampton, Massachusetts, the country was much lower than it is today, as proved by the glacial clays in that region.

Regarding this region Emerson, **1917**, writes:

"As the basin of the Connecticut became free of ice a body of water was formed so broad and deep that laminated clays were deposited in it 180 feet deep, so long lived that it has cut deep notches and developed broad deltas at its shore line, and so slow in current that the thin-layered clays were formed even through the narrows between its broader water bodies. These narrows divide the lake into the small Montague Lake; the long Hadley Lake, north and west of the Holyoke Range, extending from Greenfield south past Northampton into Connecticut; and south of the same range the Springfield Lake, 20 miles broad, reaching far south to the middle of Connecticut. The ice front still retreated northwest across the Berkshire Hills, with great lobes extending down the valleys and out into these lakes, where they calved icebergs, thrust the clays up in extreme confusion, and maintained an Arctic climate during all the life of the lake.

"The lakes are bordered by a bench, which is well marked where it cuts into sand beds or drumlins and broadens in great delta flats at the mouth of tributary valleys. Its gravels grade through sands into the laminated clays of the lake bottom. Each stratum is double. Its lower half is composed of very fine sand, which grades up into a much finer blue clay, and the change is abrupt from the top of this layer of blue clay to the bottom of the next sandy layer. In places a film of coarser sand, an incipient ripple marking, a mica scale, or fossil leaves appear at the top of the layer of clay.

"The sandy layer represents the flood waters of the opening spring and grades into the fat clay that settled from the stagnant water beneath the ice of the following winter. Each layer thus represents a year's growth. As the clays are about 180 feet deep and each layer about one-third of an inch thick, the lake may have remained about 6,000 years.

"The bench stands about 400 feet above the present sea level at the north line of the State and 200 feet above it at the south line. As there was almost no southward current in

these lakes the beach must have been nearly horizontal, and the basin in the northern part of the State must subsequently have been elevated nearly 200 feet more than on the south line." EMERSON, 1917, p. 141, 142.

In connection with the recession of the Connecticut River lobe of the Wisconsin ice sheet, a factor which has been too little considered must be mentioned. The late Professor Tarr, in a paper (1912) which was published posthumously, noted that the retreats of glaciers in which the ice fronts were in water retreated much faster than glaciers with ice fronts on the lands. He wrote:

"Under the simplest of circumstances the advance or retreat of a series of glaciers is a complex phenomenon in which so many factors are involved that a full analysis of them can not be undertaken here. Yet some of the factors stand out with such distinctness that I may take time to briefly point them out. The nature of the glacier terminus is of fundamental importance. If the end of an ice tongue is in water it makes a great difference in the rate both of advance and recession whether the water is salt or fresh, whether it is deep or shallow, whether it is in active movement or is quiet, whether there is or is not a free escape for the icebergs, and whether the relative area of ice cliff is small or great. All these factors are effective in addition to the rate of supply of ice to be discharged. If, on the other hand, the terminus is on the land, there are influences of exposure, of elevation, and of amount of moraine cover, as well as the amount of ice supplied.* * * It is clear that there must be a very great difference, especially in recession, according to whether the ice front is on the land or in the sea, for in the latter position wastage is far more rapid than in the former." TARR, 1912, p. 254.

If, during the closing stages of the Wisconsin epoch, the Connecticut River lobe had its ice front in water of considerable depth, as seems to have been the case, that part of the ice sheet would have retreated faster than the ice on the adjacent lands. If such was the case the ice front of the lake would have been located in a reëntrant of the glacier, and ice would have extended on the land southeast and southwest of it. Streams would have entered the Connecticut Lake from the east or west and possibly glacier tongues entered the lake from east or west after the lake ice front had retreated farther north. The latter may have been the case in the Wells River section. Here, it will be remembered that large sections of the clays were greatly contorted showing that the ice must have advanced over them from the northwest. Ice and glacial streams entering the lake from the side would complicate the deposition in the clays, so it is well to bear in mind the possibility of such occurrences. The locations of some of the clays and sands which at times appear to be anomalous, might be explained in this way.

The main fact to be noted is that while clays were being deposited in one part of the lake, sands or even gravels were perhaps being laid down in other

parts close by, at the same time. When a glacial stream emerges from the ice, even in deep water, the layers deposited are coarser and thicker than farther from the ice front, where the speed has diminished and conditions have become possible for the recording of seasonal units. The yearly deposit in the case of a glacial stream emerging into deep water would have a history somewhat as follows: — Commencing in the spring near the place of emergence of the glacial stream, gravel or sand would be found, a little farther away finer sand. The layer of this finer sand would grow progressively thinner and the texture would become finer as the relatively slow stream became more distant from the ice. Finally in quiet water nothing but silt and clay would be laid down, either at a long distance from the ice or nearer the ice but off to one side in quiet embayments. In the winter time the glacial stream, except in times of thaws or rains, would be almost extinct. Clay might even be deposited at the very place of emergence of the stream. Any clay thus deposited, however, would be promptly washed away in the torrents of the succeeding spring and summer. In quiet waters a slow settling of the fine clay would be in progress, interrupted perhaps by slightly coarser sediment brought down by the water of a thaw. The annual deposit, therefore, would have the shape of a wedge with the thick part near the ice and the thin part farthest away. In deep water this wedge would spread out as a fan having a spread of nearly 180°. If the glacial stream was on the west side of the valley, sands or perhaps gravels would be deposited there, while on the east side of the valley nothing but silts and clays, provided of course quiet water conditions prevailed in the east. The western deposit would be built up perhaps fifty times as much in a year as the clay deposits on the east. On account of erosion and redeposition near the ice, in the neighborhood of the place where the stream emerged, a small amount only of the fine material deposited would remain. Some such conditions must have prevailed in the lake valley of this region, during the retreatal episode of the glaciers of the time. In speaking of the continuity of the clay layers, therefore, it should be remembered that toward the glacial stream they become coarser, merging into sand or gravel at the ice, and that away from the currents or where the currents died out, they would pass into thin units.

Woodworth, **1905**, has given a good description of the nature of deposition in the case of a single stream emerging from the ice into shallow water, or on to a proglacial delta. He writes:

"For illustration the simplest case will be taken, that of a glacier discharging its drainage by a single stream into the head of a bay or lake on the border of which it has already built a

delta across whose surface the stream swings in the process of discharging its load of gravel, sand and clay.

"While the stream is aggrading its delta, it swings from side to side through the arc whose trace is the free margin or shoreline of the deposit and whose center is the mouth of the glacial stream. Take the stream at a moment when it lies at one side (say the left) of its delta contiguous to the ice front. Its burden of gravel and coarse sand enters into the construction of the delta proper. Over the bottom of the lake or bay the clays carried out in suspension are constantly coming to rest at distances from the delta margin determined by the presence and velocity of the currents and the time taken for the particles to fall through the water. For some distance over the bottom in the path of the stream-made current, the finer particles of sand which have not at once been drawn by gravity down on the delta talus will come to rest, forming a deposit of very fine sand extending outward from that part of the base of the delta. Around the remaining portion of the area confronting the delta base, clays will deposit as elsewhere over the floor of the water body. In the course of a few days or weeks or months, dependent on velocity, load, and the area of its delta fan, the stream will have moved laterally across its delta to the opposite side. The fine sands will now have been deposited over the entire area in front of the delta base while clays will have been deposited on that side where sand was previously going down. Still later, the stream will have swung back to the left of the delta and sands will be depositing along that portion of the basin floor, while clays are deposited over all the area on the right. The stream thus swings to the left and right of its delta, strewing fine sand over the bottom in advance of the delta. These changes will continue so long as the stream is building up its delta and the water body is unfilled with sediment. There will thus be built up on the floor of the basin an alternation of layers of clay and fine sand, whose stratification seen in a cross-section drawn transverse to the axis of the delta will be that shown in figure 22, in which the black line represents the sand layers, the white banding, the clays.

"Where the stream halts, the sand layer will be thicker than where the stream has moved steadily along in its lateral motion. At the extreme right and left, where the stream has halted and turned back on its course, the sand bands should be thicker than in the middle of its shifts.

"Sand partings will ordinarily be thinner than the clay partings for the reason that the fine sand is depositing over the basin only beneath the laterally shifting, stream-made current, while clays are making everywhere else in the longer time during which the stream fails to cover the much larger segment of the arc traversed by its swings. The thickness of clay layers and sand layers will be greater the slower the rate of lateral swinging of the stream; the sand layers will thicken toward the delta, the clay layers will thicken away from it; and at a distance beyond which the fine sand is carried in suspension, the deposit of clay will be from this cause alone continuous. The rate of lateral shifting will increase directly as the load carried by the stream since the excess of detritus left on the delta plain over that carried to its edge fills up the bed and causes the current to slide off on to the part not so much built up or to give off distributaries which will naturally start out from the side toward which the stream is shifting. Thus increase in load and marginal discharge will not give rise to a proportionate increase in thickness of the prodelta sand layers for the reason that the stream will not deposit sand for so long a time over a given space, because its cycles of swinging will be more rapid.

"Delta streams tend to break up into minor streams or an interlacing of streams, so that there will frequently be many lines of prodelta sand deposition, introducing minor bands of sand and clay. The breaking out and shutting off of a distributary which ends independently on the delta edge will give rise to lenticular partings of sand over the prodelta floor." WOODWORTH, 1905, p. 181–183.

Farther on (*loc. cit.* p. 183) he notes:

> "It is doubtful if the regular banding of larger bodies of clay miles beyond a delta margin with an even lamination of sandy partings can be so explained." WOODWORTH, 1905, p. 183.

In very shallow water the swinging of the stream across the delta-fan would produce a banded structure of alternating coarse and fine materials in the manner described by Woodworth. In the case of a glacial stream emerging into deep water, however, conditions would be different. The sediment-laden current would spread out to right and left and assume the shape of a fan itself. The place of emergence of the stream would shift with the retreat or advance of the ice, so that a very extensive fan of any description could not often be built up at any one place. Although in shallow water banding of a discontinuous and rather irregular nature is often due to the swinging of a stream across a delta, the cause of the regular banding discussed in this paper is principally alternately quiet and moving water.

In Rhode Island some laminated clays are well exposed in the town of Barrington in the clay-pit of the Barrington Steam Brick Co. This locality was described by Woodworth (1896) and later by Fuller (1899). The clays here are reported to be 60 feet thick. In November, 1917, about fifteen feet only of the upper part of the deposit could be seen at the workings in the pit. The laminae at the bottom of the exposed section and for about seven feet upward have a very regular interval of about one fourth of an inch. The coarse components are thick relatively to the fine, the latter not being over one fourth as thick as the former. The units increase in thickness regularly upward and at the top of the clays are an inch and a half thick. Sands lie on these upper layers and here and there may be seen lumps of clay mingled with the sand in positions which seem to indicate dislocation by moving ice. In places the clays exhibit large folds for the seven or eight upper feet of the deposit, and in some of these depressions peat several feet thick has formed. The clays also appear to be cut off on top in some places. From a number of well-glaciated pebbles found in the uppermost part of the deposit and the large glacial boulders found on the surface not far away, it is evident that ice advanced over this region after the clays were laid down. The thickening of the seasonal deposits upward appears to indicate an approach of the ice. Among all the different causes for the thickening of the seasonal deposits it is difficult to think of anything which fits this case so well as ice advance. It is possible that these clays are older by many years than the ice advance indicated by the folds; irregular

lumps of clay in the deposits above the clays; erosion of clays; and glaciated pebbles and boulders on the surface; but in most places the evidence indicates that these upper sandy beds lying on the clays were contemporaneous with the ice advance.

Banding appears to be lacking in these clays at certain places to the east of the pit now in active operation. The cause of this lack of layers has not been determined.

In regard to the alternations in the layers at Barrington, Shaler wrote:

> "The cause of these alternations has not been found. It may have been connected with the seasonal variations in the flow of water from the ice front and the consequent carrying power of the streams which did the work. In some sections there is a curious likeness in the thinness of the layers which suggests some such action." SHALER, 1896, p. 968.

If the banding in the clays means seasonal deposition there are at least 500 years represented in the small section exposed in the Barrington clay-pit. If the whole sixty feet of clays should have an average thickness of one fourth of an inch for seasonal deposits the years represented would be not less than 2,800 at this locality.

At Barrington, as has been noted, the fine components in the banding are very thin compared with the coarse components. This may mean comparatively shallow water or a short winter season. There is no indication of ripple mark. The water was not very shallow, probably not less than thirty feet deep when the latest clay units were deposited. It is also possible that the glacial streams here contained very little of the fine clay material.

4. CRITERIA FOR THE STUDY OF AQUEO-GLACIAL SEDIMENTATION.

In studying the seasonal banding in glacial sediments, the differences and irregularities in the banding of the various exposures demand explanation. Without some actual record of the formation of the layers it is impossible to do more than offer hypotheses or theories. The best way of all to determine the conditions which existed in the bottoms of the areas of deposition, would be to probe the deposits now forming in some of the existing glacial lakes and study the samples thus taken. It would also be possible to collect deposits as they form, during a period of several years. In this latter way it would be possible to identify each deposit with its year. As the weather conditions for that year and place would be recorded, the study of the layers with regard to the weather would be most profitable. Some such procedure as this would seem to be desirable if this subject of seasonal deposition in deposits is to rest on an absolutely secure scientific basis. In the meantime, all that can be done is to compare seasonal bandings with other bandings and in the case of ancient bandings in slates and sandstones, to compare them with known seasonal bandings in more recent deposits.

1. Factors determining the width and other characters of regular banding.

A. In considering the thicknesses of seasonal deposits the amounts of sediment which come from glaciers in various parts of the world must be mentioned. Other things being equal, the size of a glacial stream depends on the size of the glacier. In Alaska, for example, the streams from the large glaciers are large and the amount of sediment carried out each year is tremendous. Reid (1895) estimated that 15,600,000 cubic meters of sediment was the yearly product of the Muir glacier, from all its glacial streams. The annual product of the Unteraar glacier, in Switzerland, is only 6,000 cubic meters.

The amounts of sediment in the glacial waters are also very variable. The Muir glacier water has a very great amount of sediment in comparison with most glaciers. Wright (1891) found 12.12 grams per liter and Reid 12.98 grams per liter. Reid cites several cases as follows:— The water from the

glacier in Söndra Strömfiord, Greenland, had according to Rink (1888) .77 grams per liter. Helland (Heim, 1885, p. 363) gives the quantities of sediment in waters from many glaciers. The water of the Alangordleck glacier, Greenland, had 2.37 grams per liter. From Helland's list I copy other results from several glaciers:— Greenland, Assakak glacier, .20 grams per liter; Jacobsbain glacier, .10 grams per liter; Norway, Austerdal glacier, .056 grams per liter; Langedal glacier, .513 grams per liter. Reid also gives the amount of sediment in the Unteraar glacial waters in Switzerland as .142 grams per liter. In August, 1908, I determined the amount of sediment in the water of the Bow River at Banff, Alberta, in the Canadian Rockies and found, during warm weather, .28 grams per liter. Banff is at least twenty-five miles from glacial ice.

Reid (1895) notes that most of the sediment from the Muir glacier is deposited within a few miles of the ice front. This is due to the flocculation of the clay grains by the salt water of Glacier Bay. He even states that the yearly deposit must be as much as ten feet a year. Soundings appeared to indicate that the shallowing of the bay is going on as rapidly as that. In the case of fresh or slightly brackish water the settling is nothing like as rapid as in salt water. Fine clay grains in fresh water may remain in suspension for days and months. The experiments of E. M. Kindle (1916) are valuable in this connection.

Kindle writes:

> "Two quarts of water were thoroughly mixed with 3 cubic inches of clay and placed in two milk bottles of quart size with flaring type of neck. Two tablespoonfuls of salt were mixed with one (A), the other (B) remaining a freshwater mixture. At the end of ten minutes the flocculated clay in A had settled 2¼ inches, and the upper 2¼ inches of the mixture was clear enough to read fine print through neck of bottle. In ten minutes the sediment had settled 4½ inches, the mixture being perfectly clear in the upper part. The freshwater mixture showed no clearing during this interval. The settling was accompanied by constant upward currents of sediment all round the sides of bottle, starting from the contact of the flared and straight-sided part of the bottle. After the top of sediment had settled to the level of the straight-sided portion of bottle these upward currents on the sides ceased, and the surface of sediment at this stage was covered over by small fumarole-shaped mounds, 3 to 10 mm. in diameter, each with an opening at the summit the size of a pin-head or smaller. The B mixture showed no sign of clearing during this period. Eighteen hours after starting this experiment 2 inches of sediment had fallen to the bottom of A, and the liquid above was perfectly clear. The sediment still had the irregular miniature-mound covered surface noted above. No settling appeared to take place in B during this time. After forty hours, settling had nearly ceased in the saline mixture, leaving perfectly clear water above the 2 inches of sediment. The freshwater bottle showed its original turbidity throughout. Another freshwater mixture of this clay remained turbid after standing 2½ months. At the end of forty hours the saline mixture was thoroughly shaken and sedimentation started over again.

The phenomenon noted above was repeated as already described, except that the process was slightly more rapid than in the first case." KINDLE, 1916, p. 543.

It is evident that in fresh-water streams and lakes much sediment may be transported for many miles before settling. The coarser grains of the clay, might settle rapidly, but much of the finer material would remain in suspension for months and might not all settle, even in quiet water under ice, during a long winter.

By a study of the sedimentation it should be possible to determine whether marine or fresh-water conditions prevailed at the ice front, or in the area of deposition beyond the ice. If the glacial sediment was transported into salt water it would be logical to expect relatively thick deposits. Tidal scour, however, would probably erase anything like a regular order of deposition, except perhaps in water deep enough to be out of reach of such action. In fresh-water deposition it is evident that the thickness of seasonal deposits will depend largely on the amount of sediment supplied to an area of deposition, and also on the size and shape of the area of deposition. If the glacial waters could not travel far the deposits should be thicker than in a large body of water, where they could spread or be transported for many miles. Lake Louise in the Canadian Rockies illustrates the former case, and the Lake of Geneva in Switzerland might be given as an example of the latter. The size of the glacier will also influence the thickness of the seasonal deposits, for as already noted, other things being equal, glacial streams will always be larger from a large glacier than from a small one. In the retreat of the Wisconsin ice sheet the streams should certainly have been large. Needless to say, the temperatures would also have a most important bearing on the glacial torrents.

B. In considering the ratio between the widths of the coarse and fine components of the banding, a factor must be noted which may have an important bearing on this ratio. All tills vary somewhat in the amounts of coarse and fine sediments in their matrices. Tills with the finest materials are usually found in lowland or valley regions. On the uplands the matrix of till usually has a greater percentage of coarse material. (Emerson, 1917, p. 137). The matrix of till is sometimes almost altogether sand with very little rock-flour or clay. As most of the banded clays have their origin under glaciers, as the result of grinding, it would be natural to expect the ratio of the thicknesses of the coarse and fine components of the banding to be determined to some degree by the ratio between the coarse and fine sediment in the till. As the material of the glacial clays usually comes largely from the till of lowland or

valley regions, the fine components of the banding are usually represented by a large percentage of the finest clay. In certain cases, however, as where a glacier has over-ridden sand and gravel deposits for a long distance, the glacial streams may not contain much of the finest clay sediment.

C. To distinguish between the effects due to the composition of the till, and to effects due to climatic and other factors, in a study of the ratio between the coarse and fine components of the banding, may not be an easy matter. The true nature of the climate responsible for our Glacial periods is not well enough known to speak with certainty of the weather conditions of those times. It appears to be fairly certain, however, that high winds as denoted by loess deposits outside some glaciated areas, with much more precipitation than we have at present, was characteristic of the several glacial climates of the Pleistocene period. What the distribution of temperatures was over the year is not well determined. It is even possible that there was more heat instead of less heat from the sun, thus producing greater evaporation in the equatorial regions and greater precipitation in the northern regions than at present, with higher winds. (Tyndall, 1865, p. 205–207; Huntington, 1914, p. 477–590).

Whatever the distribution of temperatures might have been during the Glacial epochs, the seasonal layers ought to throw some light on this problem. A long cold winter ought to be recorded by a thick layer of the finest sediment, and a short summer should be recorded by a thin layer of the silt or fine sand. If the time of freeze-up were of short duration the layer of finest sediment should be thin, etc. The ratios between the thicknesses of the coarse and fine components should be studied rather than the actual thicknesses of the individual components, for the thicknesses of the layers are due to other factors in addition to the climatic factor. The ratios between coarse and fine components are also due to the relative amounts of coarse and fine materials in the till. To distinguish between these causes affecting the ratios it would be necessary to study the till from which the clay deposits were derived.

With interglacial conditions, when the temperature was above the freezing point for the greater part of the year, other things being equal, the coarse component should be thicker than the fine. If, during the winter, there were thaws of intensity sufficient to inaugurate rapid stream flow, the fine component should show evidence of such thaws in coarser, thin layers, intercalated in its midst. In case the first great thaw of the spring at the breaking up of the ice, is followed by a freeze-up, there should be found near the top of the fine component a layer

of coarse material followed by a thin layer of fine material. Above the latter would come the coarse component of the summer conditions.

D. The position of the ice front relative to the area of deposition of the banded material is of prime importance in the regulation of width of bands. Near the place where the glacial stream emerged from the ice no regular banding could be expected, even in deep water, on account of the disturbed and varying conditions on the bottom, attendant on such swift streams. At places along the ice front where quiet water prevailed, however, regular undisturbed deposition should go on with resultant regular banding. Glacial boulders should be found in the clays in such locations. On account of the greater amount of material near the places of emergence of the glacial streams, the banding should be thicker in both components than would be the case if the ice had retreated to a distance. As the ice retreated, therefore, the banding should become thinner and thinner. Conversely, if the ice were advancing the bands should become thicker and thicker.

The texture of the sediment in the coarse and fine components of the banding should vary to some extent, according to the proximity of currents. The nearer the stream of supply from the ice the coarser should be the sediment deposited. The finest glacial clays, however, have nearly the same size of grains, whether the place of deposition is within a mile of the ice front or many miles away. It has been noted above that the farther the ice has retreated from a given locality the thinner would be the deposits of any year. It does not follow, however, that the sediment of the fine component should be very much finer far from the ice than within a small distance of the ice, provided the seasonal hypothesis is the correct one, in the interpretation of the coarse and fine components of the banding. In the winter time there would be no currents in the deep water, and whether the location was one mile or twenty miles from the ice front, only the very fine clay lingering in suspension in the water would be deposited. The coarse components of the banding when not due to wind action should show a finer texture far from the ice than near. In the absence of actual data on the nature of currents of water on the bottom in fairly deep water, during times when the supply of water to a basin is abundant, it is impossible to determine this question satisfactorily.

E. Depth of water in the area of deposition would affect the width of regular banding. At the beginning of the winter season the water would contain a great amount of fine clay particles held in suspension. Such particles settle with extreme slowness. The finest particles of all would settle last.

The top of the fine component, therefore, should have the finest material. In quiet but shallow water with a depth of say fifteen feet, and with an ice covering, such as would prevent wave action, the amount of sediment which would settle to the bottom during a winter season might be practically limited to the amount contained in the water at any place when the winter freeze-up came.

In deep water of 100 or more feet, at an equal distance from the ice, the amount of sediment which would settle in a winter season would be greater than in the case of shallow water, as such deep water would contain more sediment in the beginning of the winter season. Such cases would of necessity be limited to fresh-water basins without tidal scour or other disturbing factors. As the finest clay particles settle with extreme slowness, when a thin layer of this finest clay material is found topping the fine component, it must mean that the coarser clay particles have been already deposited and that only this finest clay remained to settle. Knowing the very slow rate of settling of clay material, it might be inferred that the settling of the material contained in a seasonal layer of the glacial clays has taken months rather than weeks or days. If the seasonal layers are very thin at one place, but composed of material of the same texture as at another locality where the layers are thicker, the water in the former case may have been shallower than in the latter, provided, of course, that the place of stream emergence was equally distant in both cases. To my knowledge this cause for the thickness of layers has not not been suggested heretofore.

F. In certain very favored locations undisturbed records of the weather vicissitudes for a year or years might be preserved almost complete. The first condition for such a deposit would be a location not very far from the ice front where materials were abundant and deposition rapid enough to record minor weather fluctuations. At the same time the water should be deep and quiet enough to insure deposits already laid down, against erosion and resulting destruction of the record. Certain deposits have been made in locations approaching these ideal conditions. Records of day and night sedimentation might be partially preserved in such locations.

G. If the land near the ice front should be without ice, snow or vegetation, a high wind in the right direction, blowing over loose sand or silt, would have the power to transport sediment for miles into the basin of deposition. Some of the thin layers of fine sand found in clays or slates, which are difficult to account for, might be due to this cause. Unless the sand grains show evidence of wind action, however, such a cause would be difficult to prove (Woodworth,

1905, p. 184, 185; David and Priestley, 1908, p. 305, 306). If the wind action came at regularly recurring periods there should be regularly recurring deposits of wind-blown material in the clay layers. Loess deposits often occur adjacent to glacial deposits (Huntington, 1914, p. 575–577).

H. If vegetation flourished near the ice front, dead leaves, twigs, seeds, and spores would be washed by streams emptying into the basin of deposition, and settle to the bottom. On account of the freezing of such streams during the winter, such material would not be expected often in the winter components of banding. Emerson (1898, p. 706–710) has found such vegetation in the coarse components of the Connecticut River clays, and Coleman (1902, p. 71–79) found similar vegetation in the coarse layers near Toronto. None of this organic matter was found by them in the winter components, although such material might be found in the winter components exceptionally.[1]

2. Factors causing irregularities in banding.

The conditions of regular banding have now been discussed briefly. It is seen that to have regular banding at all, the disturbing elements must be as nearly absent as possible. In a visit to almost any glacial clay deposit it is evident at once that although regularity of interval between the layers is the rule, there may be interruptions of various kinds in the regularity.

A. Even in locations where the disturbing factors are at a minimum the grounding of icebergs may be a common occurrence. The ice in coming to rest drags over the bottom, destroys some of the upper layers and contorts many more lower down. Contorted zones produced in this way are the most common irregularities in otherwise regularly banded clays. Glaciated rock-fragments are very often found mixed in such contorted zones and a majority of such fragments are found on the top of the contorted layers sometimes in a till deposit. In some cases the contorted zones show evidence of actual ice advance. The contortions may be completely cut off on top and the contorted zone itself may have folds eight or ten feet or more from the tops to the bottoms of the arches, with a thin layer of till at the top.

The deformation of layers, intercalated between horizontal layers of the clays, may be due in many cases to shearing produced by ice, well above the

[1] It might be noted here that the extremely thin coaly laminae in parts of the Ecca shale, which lies conformably on the Dwyka tillite of South Africa, might have originated in the same manner as the peaty layers in the glacial clays.

deformed zone. The folding observed might result from the downward pressure of the ice alone, or by the dragging effects of moving ice. Inasmuch as the directions of the folds correspond in nearly every case observed in the Connecticut River clays to the direction of ice movement, I have considered it more probable that the results noted were due to ice drag than to vertical pressure alone.

It is also possible that the deformed layers in question might be the result of creep toward an unsupported edge, due to the weight of superincumbent clays alone.

Where glaciated rock-fragments are found mixed with or lying on the contorted zone, as noted above, I believe it is good evidence of deformation by contact of the ice itself, whether by icebergs or by a moving glacier. In most cases the magnitude of the deformation, together with the nature of the strata above the contorted zone, would decide which of the two kinds of ice action produced the results. Icebergs would deform the clays and pass on, without affecting the general sedimentation. If a moving glacier did the work, it is likely, although not necessary, that the strata just above the contortions would differ in thickness and texture from the layers of the contortions and those just below them.

In cases of deformation where there is no good proof of direct ice action, such as glaciated rock-fragments or till, it is often difficult or impossible to decide what caused the movements of the layers. The direction of movement of the deforming force, whatever that might have been, may eliminate one or more of the agents or methods under consideration.

B. At rare intervals a layer of rock-flour, from an inch to three or four inches thick, may be found. The true explanation of such layers is not clear. The diversion to one side of the glacial stream which supplies the material, caused by the temporary blockade of the usual channel or course by a large stranded berg, might, for a short time, transport to the locality in question much more of the rock-flour type of sediment than usual. Upon the melting of the berg and its consequent floating away the water would once more resume its normal course. Thin layers of gravel are sometimes, but rarely, met with in the midst of regular banding in the finest clays. The evident sorting of the pebbles appears to indicate temporary increased stream action also as the cause in such cases, as in the cases of rock-flour layers.

Another possible explanation for these abnormal layers of silt and gravel or sand in the midst of the regular banding of finest material, might be the

temporary existence of a glacial stream entering the basin of deposition near the place where such layers are found. On the retreat of the ice the course of this stream would shift and empty into the basin at some other point.

C. Even in the regular bands of finest clay there are often variations of considerable amounts in the thicknesses of the annual layers. These are what would naturally be expected in annual deposits. If any season should be much warmer than the normal season, the amount of water from the melting would be greatly in excess of normal and hence the stream flow would be greatly increased. As the strength of a current varies as the 6th power of the velocity, and the eroding power varies between the 3rd and 5th power, the greatly increased velocity of the stream, due to increased melting, would carry much more material into the basin of deposit than usual. As a stream has a greater capacity for fine than coarse sediment the seasonal layers of fine material should show considerable thickening as a result of an unusually warm season. The rock flour and gravel layers mentioned above might result thus.

An abnormally rainy summer would produce the same result as a warm summer. Rain has the power of melting ice with great rapidity. Whether or not it would be possible to distinguish between these two causes of increased sedimentation, it is not possible, at present, to say. Although abnormal heat or rains would produce unusual thickening of the layers, small changes in stream flow might also be registered in the deposits.

D. In some of the seasonal banding in which the layers are composed of coarser materials, there may be observed sudden changes from thick to thin layers or *vice versa.* Where such sudden changes come it is more reasonable to ascribe the change to shifts of the glacial stream from year to year than to changes in the weather. It is observed that there is a marked lack of uniformity in interval between the layers of the coarser sediments. Where the texture of the material is of sand or fine gravel, uniformity of interval between the bands is rare. Currents swift enough to deposit sand or gravel would also be strong enough to erode any bed of finer material which had been deposited. In this way the fine component would be partially or wholly lost. This erosive action combined with the shifting of the streams would complicate the bedding in such a way that it would be impossible to recognize seasonal effects. With these facts in mind it is not difficult to understand the irregular banding in deposits of alternating fine sand and silt, and sand and gravel. (See Plate 3). In spite of these highly disturbing factors in the coarser sediments, however, regular banding has been observed in alternating beds of conglomerate and slate, at Squantum. (See Plate 4).

The swinging of a stream across a delta will give rise to irregular, discontinuous, alternating coarse and fine material. Such banding must be distinguished from that which originates in front of a delta in deeper water. There may be, in certain locations, transitional zones between the delta-type of banding and seasonal-type. In case the glacial stream enters deep water on leaving the glacier, the delta-type of banding may not be found. (See p. 27).

E. In the retreat of ice fronts it is recognized that those in water deep enough for the calving of bergs, retreat much more rapidly than those on land. (Tarr, 1912, p. 19–20). Ice fronts in salt water retreat more rapidly than those in fresh. If a large ice sheet should have parts of its front in water deep enough for the formation of icebergs, and parts on land, the parts in water should occupy reëntrants in the front. In such cases streams from the land ice might enter the main basin of deposition at points miles below the part of the front in water, and mingle their sediments with the sediment from streams debouching from the part of the front in water, thus confusing the consequent stratification in the seasonal components of the banding. In such cases it would be impossible to identify the different seasonal events by means of minute characters of the banding. It should be possible, however, to distinguish winter and summer effects, but very little more.

A similar mixing of sediments would occur in the case of several branch streams from different glaciers entering a main-trunk stream which empties into a lake or other body of water. The Rhone Valley from its head in the Rhone glacier to the Lake of Geneva may be taken as an example of such a case. At least twenty streams from glacial ice enter the Rhone above the Lake of Geneva. The study of the layers in the Lake of Geneva could be of very little value as a record of the weather for any season. Winter and summer deposition, however, should be registered.

F. In the subglacial channels, stream capture must go on, in much the same manner as with rivers in general. When such a capture takes place it would be relatively sudden. In this manner the sudden increase in water of the capturing stream would cause a thickening of the seasonal layers in the area of deposition of that stream.

G. In shallow water wave action might stir up the sediment on the bottom for a short interval. When the sediment settled again there would be evidences of violation of normal deposition. Wave ripples should be found in sediments subject to wave action.

Bergs falling from an ice front would cause waves, as is the case today with all the glaciers reaching water of any depth.

H. Tidal scour would efface seasonal banding. Where the water of the sea is deep enough and the tidal action on the bottom very mild, seasonal banding might be found in marine deposits.

I. Seiches in lakes may have an influence on banding. A piling up of the water at one end of a lake by the wind might increase the depth several feet and in this way affect the sedimentation to some extent. At the opposite end of the lake the water would be slightly lower, during this time, so that sedimentation might be slightly affected there. Seiches due to other than wind effects cannot be considered here. (See Darwin, 1898, chapter 2).

J. Earthquakes are known to stir up bottom mud. Irregularities would be produced in this manner. (See Shaler, 1888, p. 408–419).

K. In Alaska, Tarr (1909) noted that the glacial streams sometimes rise suddenly without apparent cause. He suggested the breaking of a glacial dam. The falling of large ice blocks in the subglacial tunnel might very well dam the torrent temporarily. When the water overcame such a dam the torrent would rise suddenly as observed. The action of earthquakes would precipitate or cause the falling of ice blocks, although blocks would fall and do fall without such a cause. I observed a large fallen block in the tunnel of the Roseg glacier in Switzerland, in 1913.

L. Apparent lack of banding may be observed in glacial clay deposits. Is there a lack of banding in such deposits? In much of the slate underlying the tillite at Squantum Head no banding is apparent on the weathered or fresh specimens. Microscopic sections, however, reveal just as regular banding as can be found in any of the slate at Squantum. The reason for the invisibility of the banding to the naked eye is the fact that all the sediment is so fine and the difference between the texture of the coarse and fine layer is so small that it cannot be seen. Whether this explanation would account for some apparently unbanded Pleistocene clays remains to be proved.

When clays are over-ridden by advancing glaciers, the banding is often so crushed and contorted that it may not be apparent. The slate under the tillite at Squantum Head has been crushed in just this way, and this may contribute to the invisibility of the bands, but it is not thought to be the main cause.

5. THE ROXBURY CONGLOMERATE SERIES

According to the work of La Forge, the Roxbury conglomerate series is described in part as follows:

"The lower formation, named for the Roxbury district of Boston, where it is conspicuously exposed, consists of a thick conglomerate and some sandstone and slate. In at least the southern part of the basin it may be divided into three members — the Brookline conglomerate at the base, the Dorchester slate in the middle, and the Squantum tillite at the top. The later flows of the Mattapan volcanic complex, chiefly amygdaloidal melaphyre, are at several places interstratified with the Brookline and Dorchester members, but they are not known to occur in the Squantum member. It is impossible to distinguish everywhere between some of the earlier beds of the Brookline member and some of the volcanic conglomerates of the Mattapan complex, but clearly the volcanic activity began before the deposition of the Brookline and it appears to have ceased, at least in so far as surface extrusion is concerned, before the advent of the glacial conditions that marked the close of Roxbury time.

"*Brookline conglomerate member.*— This member is named from Brookline, where the rocks are extensively exposed. It consists of massive conglomerate from 500 to perhaps 2,000 feet thick, which contains some layers or pockets of sandstone and a few thin lenses of slate. At some places along the southern margin of the basin its base is a slaty or sericitic quartzite but at most places it is a coarse ill-sorted conglomerate containing some pebbles or small bowlders more than a foot through.

"*Dorchester slate member.*— This member is named from the Dorchester district of Boston, where it is exposed at several places. It consists of red and purple slates, in part cross-bedded, interbedded with sandstone and fine-pebble conglomerate. The slate is typically rather coarse grained and consists largely of reworked volcanic sediments. In Dorchester and in the southern part of the basin generally the member is 100 to 600 feet thick, but if the slate exposed in and about Allston Heights is assigned to the Dorchester member, its maximum thickness may be as much as 1,000 feet." EMERSON, 1917, p. 56, 57.

THE SQUANTUM TILLITE MEMBER. The exact sequence of the tillite beds and associated deposits at Squantum is difficult to prove for several reasons. First, the more or less continuous outcrops exhibiting few different horizons of the formation, strike along the shore, on the north of Squantum Head, and southward from these exposures except in the old quarry in the top of the hill, glacial drift covers the land. Secondly, several faults obscure the sequence, or at least make it somewhat uncertain. From the fact that practically the same sequence can be made out at the Atlantic exposure, however, I have felt fairly sure that the sequence published in a former paper is correct (Sayles, 1914, p. 155). The thickness of the tillite beds, however, was given incorrectly as 600 feet. Although the beds here are not doubled by folding the total thickness is probably not over 253 feet. Taking out the intercalated beds of conglomerate, sandstone, and slate, which were all included in the tillite formation

in the first description, there is left about 180 feet of tillite proper. There was also one thin bed of alternating slate and conglomerate layers, three feet thick, which escaped me in the first description.

The sequence in the tillite formation, as near as I have been able to make it out, is as follows:— The Dorchester slate underlies the tillite at Squantum. The strike of the slate is N. 48° E, and the dip 25° S. The first tillite bed is not over twelve feet thick. Above this comes three feet of alternating slate and conglomerate layers. On these layers there is about fifty feet of tillite followed by a bed of sandstone about twenty feet thick. Above the sandstone is a bed of tillite about eighty feet thick. Following this tillite a bed of conglomerate about fifteen feet thick, as seen in the old quarry on the hill. On this conglomerate is about fifty feet of tillite, with about twenty feet of alternating coarse and fine transition beds above it, and merging into these above comes the main slate formation, to be described. The thicknesses and the sequence given above are still provisional and must not be taken as final. Nothing but a trench through the hill will ever settle beyond question the sequence of the beds of this formation.

The tillite farther south at Squantum, described in the "Squantum tillite" under the heading "Squantum Southeast" was thought at that writing to be the same tillite formation as that found at Squantum Head. It may be, and only by a study of the structure of the whole basin can this point be decided. It should be noted that the tillite series at Squantum southeast is between 500–600 feet thick and little over 250 feet thick at Squantum Head. Such a great difference in thickness in such a short distance may be possible, but further study of the structure will be necessary to settle this point.

THE CAMBRIDGE SLATE MEMBER.[1] Emerson describes the Cambridge slate as follows:

> "The Cambridge slate, named from Cambridge, where it has been encountered in many excavations, consists of perhaps 3,500 feet of slate, shale, argillite, and some interbedded sandstone, and at or near the top about 40 feet of greenish and yellowish quartzite. Beds here and there are composed of reworked tuff. The formation is of rather uniform lithologic character, and appears to have been deposited in a body of fresh water, possibly a lake at the margin of the ice." EMERSON, 1917, p. 57, 58.

The uppermost exposure of the slate at Squantum, probably not more than 800 feet above the tillite, has a greenish tint due to a large amount of chlorite. This large percentage of chlorite in the slate might indicate that

[1] The slate south of Squantum Head is probably the Cambridge slate.

the waters which supplied this part of the slate came from an area of melaphyre under the ice. I have assumed in this paper that the Squantum slate is the equivalent of the Cambridge slate. From present knowledge it appears to be, but if it should turn out that there are two different tillite formations instead of one this slate would belong to a different horizon.

In 1911, while working on the Squantum tillite, I noted that the bands in the slate which overlies the tillite were much narrower near the highest observable part of the slate formation than near the bottom. The uppermost slate exposure appeared to have no bands at all. The reason for the gradual disappearance of the bands appeared to be in the gradual withdrawal of the glacier which supplied the material for the slate, to a great distance, thus reducing the supply to a minimum. That this highest slate had extremely fine bands was not observed until several years later. Later on, it occurred to me that this banding might be due to seasonal deposition like the banding in the glacial clays of Sweden described by de Geer. When I examined the slate with this idea in mind I was pleased to find that the phenomena described by de Geer and others in the glacial clays were also present at Squantum in the slate. The resemblance between the banding in the clays of de Geer's description, and the banding in the Squantum slate was so close that an account of these resemblances may serve to make clear some of the important points of this paper.

The slate is well exposed at two places at Squantum; at the southern extremity of the peninsula and at the northern extremity. The former will be called Squantum South and the latter is known as Squantum Head. There is also an exposure midway between the two, on the eastern side facing Quincy Bay, but as this slate all lies below high-tide level it is covered with a marine growth and the banding, although present, is difficult to study.

I recalled that there was a gradual transition at the south exposure, from the thin conglomerate lying on the tillite, through layers of sandstone and slate, to almost pure slate; and from a reinvestigation, it was clear that this transition from coarse to fine material upward was exactly like the transition which de Geer described. On the tillite lay some coarse waterlaid conglomerate with rounded pebbles, some of them eight inches in diameter. This conglomerate may be fifteen feet thick. The Pleistocene drift between it and the next exposure makes it difficult to determine whether it is one bed of conglomerate or several, separated by beds of finer material. About fifteen feet above the tillite, three feet more of conglomerate are visible, of a little finer texture, then comes a bed of sandstone four feet six inches thick. From this point upward in the

formation, beds of sandstone and slate alternate, becoming thinner and thinner. At first the alternations show some approach to regularity but they are not regular enough to be certainly classed as seasonal. About thirty feet above the tillite a pronounced regularity begins and from this point upward the banding is so regular that the seasonal theory of deposition is very plausible. (See Plates 10 and 13). Not until the sandstone layers become very fine does the banding show few irregularities, but wherever currents were strong enough to transport sand, irregularities must be expected. About 100 feet above the tillite the banding is extremely regular with fine layers of sand sometimes no thicker than the diameters of the sand grains and rarely over one eighth of an inch in thickness. Where these sandy layers are very thin, they sometimes appear to come to an end, but it would be strange if this were not so. It is inconceivable that currents of water should be so constant through different seasons as to always deposit sand where such extremely thin layers are in question. The wonder is, rather, that there was enough constancy in the conditions of deposition to deposit such thin layers of sand in the remarkably regular manner displayed at this place.

The seasonal units are here from half an inch to an inch in thickness, but rarely an inch. (See Plate 13, fig. 1). This fine banding is the uppermost outcrop at the southern Squantum exposure.

At this point one should revert to page 6 and compare the description there given with de Geer's description of the transition from coarse to fine beds in the Pleistocene deposits of Sweden. It is difficult to avoid the conclusion that the conditions of deposition in the Pleistocene deposits and these Permo-Carboniferous deposits at Squantum were the same.

After a thorough examination of the southern exposure a similar study of the northern exposure revealed the same gradual disappearance of the sandy layers in the transition from tillite to slate. Here, however, deeper water prevailed, for there are only thin beds of conglomerate alternating with slate visible, and the change from coarse to fine is more rapid. I found beds of very fine conglomerate, about fifteen or twenty feet above the tillite, alternating with beds of fine laminae of slate. The conglomerate layers, with rounded and subangular fragments averaging one sixteenth of an inch in diameter, were about six inches thick, and the series of slate laminae of about the same thickness (See Plates 4 and 6). These comparatively thick deposits came to an end after a dozen or so alternations and a series of banded slate deposits with occasional sandy layers came in. About twelve feet above the thick alternating

beds of fine conglomerate and slate laminae was a bed of tillite intercalated in the slate with rounded, angular, and subangular rock-fragments of sizes up to one foot in diameter embedded at all angles. Above this tillite bed was laminated slate, and some beds of conglomerate, one of them being as much as eighteen inches thick. Thinner beds of conglomerate alternating with laminated slate followed for about ten feet and then very regularly banded slate appeared of dark and light tints of red. From the description given it is evident that the ice retreated an indefinite distance but not very far, then advanced again as evidenced by the tillite bed in the slate. A retreat was again inaugurated and coarse beds of conglomerate alternating with beds of fine sediment followed. Finally the ice retreated to some distance and regular layers of fine sediment alternating with layers of slightly coarser sediment were laid down. About forty feet above the lowest of these regular banded slate layers, appeared another bed of tillite, about four feet thick, intercalated in the slate. As in the first bed, there were rounded, angular and subangular rock-fragments, and in addition, a large lump of slate and similar smaller lumps much contorted, the whole mass without any trace of stratification and the included fragments lying at all angles. The upper and lower contacts with the regularly banded slate were very uneven. It appeared that the ice ploughed up the clay and dragged upward into the till the lumps described. (Sayles, 1914, p. 154, 155). As already stated the banding above and below this last tillite bed has a very even interval. (See Plates 5 and 8). For the next fifty feet upward in this deposit, the slate exhibited very even banding but occasional sandy layers and contorted zones showed that the ice had not withdrawn to a great distance. At many places there were zones of folding and distortion, and in most of these zones small pebbles were included among the folded layers. (See Plate 8, fig. 2). These zones of folding gradually vanished and the occasional sandy layers also vanished, so that nothing but the dark and light red bands of slate could be seen. It appeared that these dark and light bands might mean finer and coarser sediment and a subsequent examination of thin sections proved this to be the case. Progressing upward the bands became gradually thinner until the exposure came to an end just north of the viaduct. There is a break in the slate series here between outcrops of about 150 yards. South of the viaduct and by the side of a huge Pleistocene boulder of Roxbury conglomerate, there was another slate outcrop with banding somewhat finer than on the north of the viaduct. What has happened between these outcrops in the structural relations of the slate it is difficult to say. There was another break in the observations, of

about fifty yards, to the next outcrop. Here the banding was seen to be very much finer. The outcropping of this very fine banding was continuous for about 100 yards and the banding at the highest observable part of the formation was extremely fine, the unit of fine and coarse layers not being over 1/32 of an inch thick.

I have described what I saw during the examination of these two exposures at Squantum, and it took several visits to observe all the features spoken of in this description.

STRUCTURE OF THE BANDING IN THE SLATE. For the proper understanding of the origin and structural character of the banding in the slate the examination of the deposits in the field must be supplemented by a study of microscopic sections. In a general way I have sketched the nature of the layers which make up the banding and other phenomena which are associated with the banding, such as contorted zones, tillite beds, etc. It remains now to describe the banding in more detail as it is seen in thin sections under the microscope.

In a previous paper (1916, p. 168) I showed that the slate was surely derived from the tillite or from material of the same origin and character. The mineralogical composition of the tillite and slate is identical. My colleague, Prof. J. E. Wolff, examined specimens of both and found the following minerals in each:— quartz, feldspar, sericite, epidote, melaphyre, chlorite, limonite, pyrite, quartzite, and calcite. The sizes of the grains range from 1/12 mm. to as fine as 1/1100 mm. The shapes of the grains are angular as in ordinary fine, glacial sediments. The fact that the tillite and slate have the same mineralogical composition and shapes of particles, does not in itself prove that the slate came from the tillite. Two beds of tillite intercalated in the slate, however, together with other evidence in the banding, prove this origin.

In 1916, I described the general structure of the fine and coarse components of the banding of the slate as follows:

> "The microscope reveals the fact that the dark layers are composed of much finer material than the light layers. The coarse layers all, without exception so far as observed, have very fine wavy lines of bedding which are cut off and uneven in places, while the fine layers are solid in appearance without these characteristic lines. The finest part of the fine layer is usually in contact with the coarse layer upward, and the change from fine to coarse is abrupt. The change from coarse to fine is more gradual upward, as a rule, and not abrupt. These layers or bands alternate with much regularity and at any given horizon their thicknesses also show regularity." SAYLES, 1916, p. 168.

This description applies to the slate above the tillite where regular banding makes its appearance. (See Plate 16). Such characters also appear in some

of the slate under the tillite. It might be added that the same characters appear in the slate at most other places where the Cambridge or Dorchester formations occur. The localities in question from which slate has been examined microscopically are:— Crow Point, in Hingham, Newton, Brighton, Cambridge, and Somerville. These slates will be discussed later. After two years' observation, it is not necessary to change the above description of the typical characters of the banding. Various irregularities intrude themselves, and await explanation and these will be considered in their proper places.

As has been stated, the fine components of the banding begin gradually to grow finer and continue to become finer in texture, until at the top the very finest material of all is found in a well-defined layer. (See Plate 16, fig. 2). This topmost layer frequently has microscopic ripple-mark on its upper surface, indicating the change to conditions of water in motion. Sometimes this almost universal layer of extremely fine sediment by which it is always possible to recognize top from bottom, is absent. In such rare cases it is evident that water currents of the high-water phase have washed this finest sediment away. Such currents might not have a velocity of over four inches a second but that would be enough to erode the finest clay. The sizes of the particles of the fine components average about 1/800 mm. in diameter with here and there larger fragments. The finest fragments are about 1/1100 mm. in diameter.

In the midst of the fine components there sometimes occur very thin layers of coarser material. This might mean a thaw in a winter season with resulting higher water. In the middle of the slate formation the fine components sometimes show these intercalated coarse layers.

The coarse components of the banding do not exhibit such a compact and homogeneous nature as the fine. As has already been stated, they consist of alternating layers or remnants of layers of coarser and finer sediment and although the fragments are fine, with some as fine as any found in the fine components, the material as a whole is much coarser than that in the fine components. (See Plate 16). Grains as large as 1/12 mm. are common, although grains of this size do not make up the bulk of these components. From the broken nature of the layers it is clear that deposition and erosion went on alternately. What was deposited on one day might be mostly eroded the following day. A count of these alternations, using all the sections I have at present, gives an average of about forty for a coarse component. They run as high as sixty and as low as twenty-four. The continual erosion of layers deposited would destroy the complete record of the alternations. The resulting coarse components of

the banding, therefore, tell only part of the story. As has already been suggested in the discussion of the clays (p. 36), ideal conditions might exist in which an almost complete record might be preserved of the alternations.

As to the cause of these extremely fine alternations, the difference in the flow of water of day and night might possibly explain them. (See Plate 16, fig. 4). Occasional thicker layers of coarse material such as are sometimes found might indicate storms of rain or unusually hot weather. In such cases many of the finer layers, due possibly to the day and night cause, might be eroded. It is interesting to note that the sections showing the most complete record of the finest layers have also the largest number, and these are in a more perfect condition of preservation than in those sections where erosion has greatly destroyed the regular order. This statement is made guardedly, as too few sections with comparatively undisturbed layers have been found to make generalizations. The quieter and deeper the water, therefore, up to a certain distance from the ice front, the thicker and more perfect should be the components of the banding, and the finer the sediment. Beyond the point of maximum deposition in deep, quiet water, the sediment should be fine but the layers thinner.

A characteristic of the first 100 feet of the slate is the formation of dendritic forms of limonite along thin sandy layers of the slate. These sandy but very thin layers usually come near the top of the coarse component in the banding, although they may occur in the fine components as well. The average size of grain of this coarse layer is slightly coarser than the average size of grain in the regular coarse component. I have thought that water percolating along these thin layers has deoxidized the iron in the material and deposited the oxide above and below in the finer material in dendritic forms of limonite. Dendritic forms occur in the coarse layer itself, leaving most of the material without iron. This dendritic material gives the effect of a very dark band, and although fairly regular in its occurrence, is not to be confused with the dark layers composing the fine components.

The reason for the occurrence of this fine layer of coarser material in the midst of the coarse component might indicate the warmest part of a season with resulting high water in the glacial streams. If there had been land without ice or snow near the ice front high winds might have blown fine sand in appreciable amounts into the water. Some of the grains are too large to be classed as clay or silt. (David and Priestley, 1909, p. 305). As observed above, the layers in question usually but not always come near the top of the coarse com-

ponent and might indicate such high winds, as are common today, at the beginning of pronounced cyclonic and anticyclonic atmospheric control in the fall. The fairly regular occurrence of these coarse layers would indicate a regularly recurring cause. Seasonal changes of temperature or periods of high wind, therefore, would explain regular recurrences of phenomena such as have been described better than anything which has suggested itself.

The sediment in the finest glacial clays is, on the whole, finer than in the glacial slate at Squantum, although as fine sediment may be found in the slate as in the clays. This would seem to indicate that this particular slate was deposited in water with a slightly greater movement than in the case of the clays. The sediment in the slate is of about the same texture as that found in the seasonal banding at North Bath and Lisbon in the Ammonoosuc Valley, already described (p. 24; also Plate 3). Some banded slate taken from the subway excavation at Harvard Square has as fine a texture as the Woodsville clay and the banding is as regular as any seen in the glacial clays. Almost all the slate of the Cambridge formation found in Cambridge and Somerville is of very fine texture, the grains averaging about 1/1000 mm. with some 1/1200 mm. This would indicate that the water was deeper there than at Squantum. The sublacustrine origin of some of the tillite recently found by Woodworth in Watertown, would also indicate deeper water than that at Squantum. (Upham, 1896, p. 371–375).

In the clay-pit of E. M. Lamarre at Woodsville, already described (p. 18) there are contorted zones between undisturbed layers in the clays. At Squantum similar contorted zones may be seen. Mr. Lahee called my attention to these several years ago. (See Lahee, 1914, p. 786–790). In Figure 1, no. 2, I have sketched the mode of occurrence of these folded and crushed layers. If this figure is compared with Figure 1, no. 1, the similarities of the two sections will be apparent at once. First of all, it should be noted that the contorted zones in the Woodsville clays are, on the whole, thicker than at Squantum. At Squantum the water was probably not as deep as at Woodsville, and could not float as large icebergs as could be floated at Woodsville. This inference is favored by the fact that the sediment at Woodsville is somewhat finer than at Squantum. It should also be noted that the contorted zones grow thinner upward, indicating possibly a retreating ice front, and hence, on account of melting, smaller and smaller bergs at this spot.

Pebbles are frequently found embedded in the contorted layers. The finding of such pebbles in the contortions of the glacial clays and in these similar

contortions, together with all the other similarities of the Squantum and Woodsville deposits, would appear to be conclusive evidence of the similar origin of the two deposits.

The slate under the tillite, of the Dorchester member of the Roxbury formation at Squantum, shows regular fine and coarse components, in specimens taken about twenty-five feet below the tillite. The sediment is coarser, in most of this slate near the bottom of the tillite, than in the slate above the tillite. This fact probably explains the lack of regular intervals in the banding, which has been observed in a number of the microscopic sections. The currents were so swift that the fine material was not allowed to remain as deposited. Evidence of this is found in some layers of the fine material which have been penetrated by the coarse sediment, the latter lying in pockets in the upper part of the fine layer. Other evidence of this current action is found in small fragments of layers of fine material which has been swept up and included in the coarse material.

This lower slate was greatly contorted by over-riding ice. Only a few specimens have been found which are free of contortions. The contortions may be found as low as fifty or sixty feet below the tillite. About this horizon the sediment of the banding is much finer than near the tillite and as fine as any sediment found in the slate above the tillite, and shows, under the microscope, regular banding. (See p. 41).

At Crow Point the slate in Huit's Cove shows regular banding in microscopic sections, and also without the aid of the microscope in alternating slaty and sandy layers. Near the deposit believed to be tillite (Sayles, 1914, p. 159) the slate shows no good banding to the naked eye, but with the microscope regular banding of fine and coarse components shows very well. The sediment is extremely fine and would seem to indicate quiet and possibly deep water. It is probable therefore, that this tillite is sublacustrine in origin. If it is not, the chances are that this slate lies under the tillite. The attitude of the specimens from which the microscopic sections were made was not marked, so further sections must be made to determine the position of the formation. As noted above (p. 48), it is invariably true that the finest part of the fine components is on top. (See Plate 16, fig. 2).

On the point which forms the northern part of Huit's Cove occur some alternating sand and slate layers. Regular banding of similar nature may be found along the shore to the north.

The slate at Brighton is banded and the bands show regular intervals

between fine and coarse components. There is some question still as to the exact horizon of this slate. It may be the Dorchester slate member of the Roxbury series. The bands are thin, not over one eighth of an inch thick. They have been disturbed by wave or current action along the bottom as shown under the microscope by small ripple-mark, and by large size ripples found frequently at this locality. The water was evidently shallow, although deep, and quiet enough for the deposition of clays.

6. BANDED SLATES WITH OTHER TILLITES.

After working for nearly two years on the problem in hand, and convinced that I was the first to suggest seasonal banding in slate connected with tillite, it appeared that Dr. Thore G. Halle of the University of Upsala had anticipated me by four years in the theory of seasonal deposition in the glacial slate. I had heard of Halle's work on the tillite of the Falkland Islands, but was not aware that he had described the banded slate which occurs with the tillite, and American geologists generally seem to have overlooked the same. Halle after describing the tillite gives a detailed account of the banded slate. Part of his description is as follows:

"Another example of rapid changes in the sedimentation can be noted in a certain kind of claystone, which occurs in typical development near the settlement of Darwin Harbour. It is worked at this place in a small quarry near the beach, and is used for building purposes. The rock, which is nearly horizontally bedded, shows a marked lamination caused by the alternation of differently coloured zones. The alternation of the zones is a fairly regular one, one yellowish brown and one dark-grey zone, forming together one layer, or marking one cycle of sedimentation. The thickness of each stratum of two zones varies considerably, generally between some few millimetres and one centimetre. On a microscopical examination of a section of this rock it is seen that the brown or yellow zone is formed of much coarser material, angular or but little rounded quartz-grains being abundantly mixed in the denser matrix. The dark-grey zone, which often has a shade of green, consists of purer, fine argillaceous material. The whole appearance of this rock is strongly suggestive of the well-known seasonally laminated clays from the areas of Diluvial glaciation. In these clays, each stratum is generally understood to represent the sedimentation of one year. The coarser grained brown or yellow zone, formed during the melting of the ice in spring and summer, passes gradually into the dark-grey zone corresponding to a slower sedimentation, and borders this, with a sharply-defined limit, on the lower zone of the following year. In the claystone of Darwin Harbour the limits between the zones are not so regularly marked, and it is not always possible to distinguish between a gradual change from brown to grey, and the rapid one from grey to brown. Yet, the resemblance to the real seasonal clays is great, and it seems probable that this Permo-Carboniferous clay owes its peculiar lamination to a succession of annual layers. At any rate, a certain periodicity in the sedimentation is undubitable." Halle, 1912, p. 159, 160.

The illustrations which Halle shows are strikingly similar to the Squantum slate, and one of these cuts is reproduced here (Fig. 2). It was very natural that Halle should have thought of the similarity between the banded slates and the laminated glacial clays. He was without doubt very familiar with the work of de Geer and also had a personal knowledge of the glacial clays.

Fig. 2. Laminated claystone. Darwin Harbour. From Halle: Bull. Geol. inst. Univ. Upsala, 1912, **11**.

In 1912 Sederholm of Sweden advanced the seasonal theory to account for banding in the Bothnian schists. There is one important difference between the work of Halle and Sederholm. The former had some undoubted glacial beds closely related to his banded slate, while the latter just assumed that the banding in the Bothnian schists was of an annual nature and resembled the banding in glacial clays. In the former case the evidence is much easier to accept than in the latter. In writing of the banding in the Bothnian Schists Sederholm records:

"Among the Bothnian schists of Tammerfors occur some whose regular alternation of sandy and clayish beds recalls very much that of the glacial clays of the same region, and is very probably, like that, due to an *alternation of seasons.*" SEDERHOLM, 1912, p. 687.

This observation of Sederholm's although very important lacks the firm foundation on which the observations of Halle rest, namely, tillite beds.

After discovering that banded slates are associated with two tillites in widely separated parts of the earth, it is natural to inquire at once whether other tillites may not have such related slates. After a conference with A. P. Coleman of Toronto, I find that the lower Huronian tillite at Cobalt is very similar to the banded slates at Squantum. Barrell (1915, p. 112, 113) mentions these Cobalt slates at the foot of Cobalt Lake.

Recently I noticed in the Geological Museum at Harvard, a specimen which had been on exhibition for about ten years but which had not been particularly significant heretofore. In 1906, Mr. A. W. Rogers, Director of the Geological Survey of South Africa, very kindly sent a set of specimens of tillite from the Griqua Town series of South Africa. The specimen in question is a well-banded black and brown jasper. The banding is so regular that in view of the

banding mentioned with other tillites, this specimen is especially important. It may be well to quote Hatch and Corstorphine on this formation:

> "The Griqua Town series is divided by Mr. Rogers into an upper group, consisting largely of slaty rocks, together with some brown and red jasperoid rocks and thin beds of chert and limestone; a middle group, consisting for the main part of the Ongeluk volcanic beds, together with some banded jasper beds; and a lower group, comprising banded jaspers, quartzites, and mudstones. The conglomeratic rocks that occur at or near the top of the lower group in the Hay district contain 'striated and flattened pebbles and boulders,' which, according to Rogers, 'certainly owe their characteristic shape and scratches to glacial action." HATCH & CORSTORPHINE, 1909, p. 148.

Concerning the sediments which lie just above the tillite, Rogers (1906) notes:

> "At Monjam, Mabedi, there are some twelve feet of thin-bedded dark quartzitic rock lying between the highest outcrops of the glacial beds and the lowest Ongeluk lavas." ROGERS, 1906, p. 43.

The age of this glacial series is still in question, but Rogers proves that it is older than the Dwyka and it is possible that it may be as old as pre-Cambrian. It looks very much as if these banded metamorphosed sediments might have the same origin as the Squantum banded glacial clays.

The ancient tillite discovered by Reusch in Varanger Fiord, Norway, rests on a sandstone which was already consolidated at the time of the deposition of the tillite as shown by well-marked glacial grooves on its upper surface (Strahan, 1897, p. 137–146). This tillite is overlain by a sandstone of a "regularly bedded" nature. Although there is no description of alternating coarse and thin beds, they may be present. This tillite is of unknown age but probably pre-Cambrian.

Lying on the Cambrian or pre-Cambrian tillite which Willis and Blackwelder discovered at Nan-t'ou on the Yangtse River in China is a thin sheet of conglomerate (Willis, 1907). Above this conglomerate comes about 250 feet of rather thin-bedded argillaceous limestones. Whether there is good banding similar to that I have described it is not possible to say. It is very evident, however, that this tillite reached sea-level as determined by marine fossils, and it is more than likely that wave action or tidal scour destroyed most of the lamination, for Blackwelder mentions only a few feet of lamination above the conglomerate.

In South Australia near Adelaide, Howchin describes the tillite of lower Cambrian age as follows:

"The lower members, beginning with the Brighton limestone, near Adelaide, show the following succession in descending order: Brighton limestone, Tapley's Hill ribbon-slates, Glacial till, Glen Osmond slates and quartzites, Upper phyllites, Black Hill (thick) quartzite, Lower phyllites, River Torrens limestone, Basal grits and conglomerates resting unconformably on a pre-Cambrian complex. The lower Cambrian beds are apparently destitute of organic remains, except for a few obscure traces of Radiolaria in the siliceous limestones." Howchin, 1912, p. 194.

The ribbon slates spoken of are certainly banded slates. The Glen Osmond slates and quartzites also show banding. It will be very profitable to reëxamine this formation.

When we come to the Permian period the tillites are much more numerous. It will be well to begin with Ramsey's Permian breccias of the Midlands of England. Ramsey was the first to consider the glacial origin of ancient consolidated deposits. In 1855 he gave notable evidence to prove the glacial origin of the Permian breccias. A description of this Permian breccia had already been made by John Phillips in 1848; he gives a very interesting account of the Haffield conglomerate which belongs to this same series. A part of the description is as follows:

"Along this line of road an excellent section is made, which on the west shows the Haffield conglomerate; above this a great thickness of new red sandstone, with its usual complication of variously-inclined laminæ, and on the eastern side red and green marls with thin sandstones. The conglomerate dips to the south-east (13°); the laminæ of the sandstone also are inclined in that direction (from 5° to 28°); the superincumbent marls and thin sandstones are greatly disturbed, in places vertical, bent, arched, and broken by faults. * * *

"Combining the observations which have now been mentioned, touching the Haffield conglomerate, it appears that the accumulation of the pebbly components of this rock is, if not confined to the localities or districts which have been named, at least nowhere else apparent at the surface. It is worthy of remark, that these points are all in situations which were or may be believed to have been bays or sheltered parts of the ancient sea-coast line; that the constituent fragments which abound in the conglomerate are very rarely rolled to spheroidal masses, and often only blunted at the angles; and that the two most conspicuous masses, viz., that south of the Malverns and that of the Teme Valley, decline rapidly toward the south." Phillips, 1848, p. 113.

Although Ramsey's breccia was the first tillite identified in the world, the Blanford brothers discovered a tillite of Permo-Carboniferous age in India, not far from Calcutta, in 1856. Above this tillite are some well-banded sandstones and shales. Describing the beds overlying the Talchir tillite Blanford writes:

"An obliquely measured section in a nullah near Purongo seems to show that in that place it is about 200 feet; here there are alternations of coarse and shaly sandstones, much

rippled (the ripples indicating a current from the North) and having occasional thin beds of shale interstratified." BLANFORD, ET AL., 1859, p. 51.

Farther on (*loc. cit.*, p. 53) Blanford writes:

> "If the deposit of shale were thick, it might resist disturbing action, and after a certain period, during a gradual depression, a regular alternation of bands of shale and sandstone might be produced, such as is frequently seen in the beds in question."

As this Talchir tillite is only 20° north of the equator it has always been one of the greatest stumbling blocks to the theorists who have attempted to explain the cause or causes of Glacial periods. If the banding noted by Blanford is really due to seasonal changes and deposition, it will be necessary now to explain not only the former presence of the great ice sheet in the Tropics but marked alternations of seasons also. The state of mind of geologists in regard to the difficulties in explaining the Permo-Carboniferous glaciation was well expressed by Prof. James Geikie in a letter to me. He wrote January 1911:

> "The problem of the Permian or Permo-Carboniferous glacial period is a hard one. It would seem to have been even more excessive than that of Post-tertiary times, and no explanation of its cause hitherto advanced seems to me at all satisfactory."

In the Permo-Carboniferous glacial beds at Bacchus Marsh a short distance north of Melbourne, Australia, there are some stratified mudstones which, from the description, appear to resemble in one respect at least the slate under the tillite at Squantum. A description by Officer and Hogg reads in part as follows:

> "*Stratified mudstones.* The beds are first described, as they form the lowest of the glacial series visible in our district. They consist of regularly stratified deposits of a more or less hard tenacious clay; they are occasionally finely laminated; they vary somewhat in colour, blue and yellow being the prevailing tints." OFFICER AND HOGG, 1898, p. 181.

It is apparent that these mudstones show banding and the alternations of color spoken of strengthens this view.

An earlier description of these same mudstones reveals contortions similar to those in the Squantum lower slate. I quote Sweet and Brittlebank as follows:

> "As has been before remarked, the mudstones, conglomerates, and sandstones alternate with each other in repeated succession — now in thick beds, now in thin beds, now highly laminated, then for short distances disturbed and distorted, with the stratification obscured, and this is repeated over several miles of country in the direction of the dip as well as along the strike." SWEET AND BRITTLEBANK, 1894, p. 384, 385.

In the Permo-Carboniferous glacial beds at Winyard near Table Cape, Tasmania, there are apparently fine banded sediments above the tillite. David described these beds in 1908 and reported four different types of rock in the glacial beds. From below upwards these beds are as follows:

> "(1) The glacial till, resembling the boulder clays of late Cainozoic age of the Northern Hemisphere.
>
> "(2) Conglomerates, frequently containing erratics and striated boulders.
>
> "(3) Sandstones, with occasional — but rare — striated boulders.
>
> "(4) Thin-bedded, often minutely lamellated, clay shales with intercalated thin flaggy sandstones, and occasionally thin bands, 1 in. to 2 in. only, of boulder clay. The flaggy sandstones and mudstones are in many cases beautifully ripple-marked." David, 1908, p. 275.

The account of these laminated slates and sandstones with occasional thin bands of boulder clay describes the conditions at Squantum. The same kind of thin layers of boulder clay are found in the Connecticut River clays and at Squantum. It is safe to say that the conditions attending the deposition of these sediments in Tasmania must have been very similar to the conditions at Squantum.

When we come to the Dwyka tillite of South Africa the literature is plentiful but detailed accounts of the stratified deposits associated with the tillite are rare. Most of the writers confine their attention strictly to the glacial origin of the conglomerate and do not mention the slates and sandstones particularly. Two writers, however, Mellor and Molengraaff, describe the beds in the upper part of the tillite and in the overlying Ecca series thoroughly. Mellor (1905) writes in part as follows:

> "With the upper portions of the Conglomerate are sometimes locally associated beds of massive sandstone, and lenticular patches of white and cream-coloured shales and mudstones, which appear to have been deposited in 'pockets' in the Conglomerate and to consist of the finest glacial mud. In a section exposed on the banks of the Bronkhorst Spruit, immediately south of the railway-line, a thickness of 6 feet of these fine white shales and mudstones occurs, consisting of a succession of extremely-regular laminæ varying from a tenth of an inch to an inch and a half in thickness. The laminæ are readily separated one from the other.* * * I have not hitherto found anything in the nature of fossils among these finely-laminated mudstones, although they would be admirably adapted for the preservation of vegetable-remains, such as frequently occur in the shales and sandstones which succeed the glacial beds." Mellor, 1905, p. 685.

Molengraaff (1898) had indeed gone more into detail even than Mellor. His description is well worth quoting, as showing close relations between the tillite and a part of the overlying Ecca beds. He writes in part as follows:

"Where the stratified beds of the Dwyka are devoid of pebbles, they are in places exactly similar to and really not to be distinguished from the Ecca shales, overlying the Dwyka Conglomerate. The Dwyka Conglomerate passes gradually into the Ecca shales and there is no real difference whatever between the matrix of the Dwyka Conglomerate and the material of the Ecca shales. The Ecca beds are entirely devoid of pebbles, with the exception of some rare big boulders found in places as will later be mentioned, and they are made up of very fine, almost impalpable mud. The bulk of the formation consists of black clay shale, the typical Ecca shale, crumbling into small pieces by a kind of spheroidal or concretionary structure, so that it is hardly possible to get from this shale a piece of a few square inches surface without cracks. Alternating with these typical black crumbling shales occur mudstones in well defined layers, the debris of which sometimes afford a good building material. * * * All the characteristics of the Ecca beds are found again in some parts of the stratified Dwyka Conglomerate, and lithologically we might speak of an inter-stratification of these Dwyka Conglomerate layers with true Ecca beds." MOLENGRAAF, 1898, p. 107.

Blackwelder found large boulders in a regularly stratified slate, and in his paper on the glacial origin of a slate in Alaska he writes:

"The large size and the variations in both size and composition among the bowlders seem incompatible with the hypothesis that the beds have been formed entirely by aqueous currents. The subangular yet irregular shapes of the bodies are also more suggestive of glacial origin than of any other. There is one feature of the formation which is sufficient, however, to prove that even if glacial it is not an ancient deposit of till or moraine, namely, the distinct stratification. The shale matrix was evidently accumulated in quiet waters where conditions favored the settling of clays and silts in successive horizontal layers." BLACKWELDER, 1907, p. 13.

Using the regularly banded deposits as a criterion for glaciation it would appear almost certain that the slate which Blackwelder described is of glacial origin. The age of the slate is still a matter of uncertainty. Ulrich considers it of Jurassic age and C. W. Wright that it belongs to the late Carboniferous.

In 1915 Atwood discovered tillite of early Eocene age in southwestern Colorado; he tells me that the mancos shale which underlies the tillite has very regular banding. Regarding the matrix of the tillite he writes:

"The matrix of this lower or yellow till is sand and clay, and it is quite probable that most of the clay was derived from the underlying Mancos shale. The sand may have come from various formations." ATWOOD, 1915, p. 17.

7. CONCLUSIONS

In view of the fact that some geologists doubt the seasonal nature of the banding in the glacial clays, it may be well to examine the evidence for the seasonal theory before passing judgment on the seasonal origin of parts of the glacial slate at Squantum, and the same slate in other parts of the Boston basin.

De Geer found that each pair of coarse and fine components of the banding was connected with a small annual moraine. These moraines were from 200 to 300 meters apart. The geologists who were with de Geer when he exhibited and explained his evidence in the field, during the International Geological Congress at Stockholm in 1910, saw for themselves that he was justified in his contentions. (See p. 6).

To rule out those agencies which cannot produce banding of the nature found in the glacial clays, may help to clear the way for any cause capable of producing the regular alternations of coarse and fine sediment found. The main factors which can produce differential aqueo-glacial sedimentation are:—the swinging of a stream across a delta; the difference of day and night melting of glaciers; more or less regular cyclonic and anticyclonic conditions during part of the year, with or without rain or high winds; periodic or seasonal winds capable of transporting sediment; tides; and the alternating conditions of summer and winter.

As has already been noted, a stream swinging across a delta may deposit alternating, irregular, and discontinuous layers of coarse and fine sediment. These are not to be confounded with the alternating layers in deeper water in front of deltas, believed to be of seasonal origin.

If the regular alternations of coarse and fine sediment of the deeper waters are due to day and night stream flow from the glaciers, what caused the minute but well-defined alternations in the coarse components of the banding as made out by Berkey in the Grantsburg clays? These layers as described by Berkey give every evidence of deposition by moving water, with periods of quiet water intervening. The structure of this minute banding did not suggest to Berkey gentle wave action on the bottom. It would be impossible for the amounts of fine clay found in the average fine components of the banding to settle in twelve hours. It is much more reasonable to believe that these minute laminae in the coarse components mean day and night effects than to ascribe this cause to the larger units of the banding. Berkey gives the best account

of the minute structure of the banding in the clays which has been published. His evidence has a most important bearing in favor of the theory of seasonal deposition.

Cyclonic and anticyclonic conditions, although fairly regular during parts of the year, with an average period of about seven days, are too irregular, when the whole year is considered, to produce the regular banding seen in the clays. If the coarse components of the banding are due to gentle wave action on the bottom, and the fine layer above is due to the settling of the sediment after the storm, how can the layers show such even thicknesses? Wave action produced by storms varies enormously in intensity. Furthermore, if the fine component means settling after a storm, and nothing more, what record is there left of the winter period? If there were seasons during glacial and interglacial times surely the deposits should show some record of them. It must also be noted that wave action of sufficient intensity to stir up one tenth of the amount of fine sediment found in the fine components of the banding is not even suggested in the layers of the coarse components. The disturbances noted in the coarse components denote extremely gentle action, and there is every reason to believe this was current action.

Although wind action of a regular seasonal nature is very possibly responsible for some of the material and for certain definite layers of coarse sediment intercalated in the banding, the findings of Berkey in the coarse components of the Grantsburg clays appear to show conclusively that currents of water were responsible for the coarse components of the banding as a whole, whether or not some of the coarse material reached the basin of deposition by the wind or by glacial streams. In either case seasonal deposition would be indicated, for in the winter the water body would be frozen over and no wind-blown sediment could be deposited in the water at that time. On account of the juxtaposition of some glacial and loess deposits it is not at all unlikely that the wind played an important part in the seasonal deposition. (See p. 36).

It is very evident that tidal action had nothing to do with the clays at Grantsburg. The laminated glacial clays here and in other places, present, as far as can be observed, the same details of structure.

De Geer, Emerson, Taylor, Berkey, and others have written about the seasonal deposition of clays in widely separated regions, and their accounts have been quoted. It remains to note one point which has not been sufficiently appreciated by those who have studied the clays. I refer to the layers in the clays described by Emerson and Coleman which contain leaves, twigs, spruce

needles, beetle wings, etc. (Emerson, see *ante*, p. 10; Coleman, see *ante*, p. 11). It was noted by Emerson and Coleman that the vegetable material was almost always found in the coarse components of the banding. Streams draining wooded areas beyond the ice front washed the leaves and other material into the basin of deposition during the spring, summer, and fall months of stream flow. It is evident also that the wind must have blown leaves and other light material, such as spores and seeds, into the waters of the basin. Leaves and other material may also have fallen from the trees directly into the water along the margin of the basin. (Jeffrey, 1915, p. 218–230). In the winter the streams were frozen and an ice covering over the water of the basin prevented leaves and other vegetal materials from finding their way to the lake bottom. Occasional leaves and twigs might reach the basin during thaws in the winter, but most of the material would be deposited during the months of stream flow of spring, summer, and fall. This appears to be the most logical explanation of the presence of organic material in the clays. If the fine components of the banding were deposited in summer as well as winter, as many leaves and twigs would be found in them as in the coarse components. Coleman found wings of beetles in the Don River clays and these would appear to indicate summer deposition. Although Emerson and Coleman mention their findings in a brief description only, their significance in the argument for seasonal deposition is most important. How these leaves, twigs, spruce needles, and beetle wings in the silty layers of the clays can be explained, except on the seasonal theory, it is difficult to understand.

In this paper the descriptions of the clays and slates have been given entirely from the standpoint of seasonal deposition. As far as the clays are concerned I feel convinced that the seasonal theory is in a very strong position and that the danger of its being abandoned is slight. When the Squantum slate is considered and the details of its structure compared with the banded clays, especially the Grantsburg clays of Pleistocene age described by Berkey, I feel very strongly that the origin of the banding in the slate is the same as in the clays. It is too soon, perhaps, to affirm finally that seasonal banding exists in the slate, although the similarities in the slate and clays are beyond question. Not only is the structure the same but the attendant phenomena plainly show the same origin. There are localities in the Boston region where this Cambridge slate formation outcrops, in which the regularity in the intervals of the banding is slight. In the Mystic quarries there is regular banding, irregular banding, and slate with no apparent banding. It is not certain, however, that this

slate belongs to just the same age as the Squantum slate. All these other outcrops of the Cambridge slate need very much more study in order to identify horizons, for it is very evident that climatic conditions suitable for seasonal deposition in one part of a slate formation might not exist in another part. Furthermore, slate without apparent banding may be well banded, as the experience with the slate under the tillite at Squantum has shown. (See p. 41).

It is needless to go over the points of similarity between the structure of the Grantsburg clays as described by Berkey and my description of the structure of the Squantum slate. If there is any difference in the structure of the two it is not possible, after reading Berkey's description, to discover it. Professor Berkey has not seen the slate *in situ* but he has some of the photomicrographs, and believes that I am justified in interpreting the features shown in the slate as similar to those of the banded clays. Mr. Frank B. Taylor spent two days with me examining the slate formation and the microscopic sections of the banding. He has been kind enough to allow me to quote his opinion which is as follows:

> "I am not only willing to be mentioned as a visitor to your Squantum locality, but would be glad to be listed among those who believe in the general correctness of your interpretation of the banded slates as due to seasonal variations."

Professor Barrell has spoken with enthusiasm of the banded slate at Squantum; he considers (1917, p. 828, 902) the structure of the slate banding and clay banding the same. Professor Hobbs, who was with de Geer on the 1910 field trip to the Swedish localities, has stated (1916, p. 112) his opinion regarding the similarity between the Squantum slate and the banded clays.

Evidence of seasons in the Permo-Carboniferous have come from New South Wales, Australia, in the discovery of annual rings of growth in trees of Permian age. (Shirley, 1898, p. 14, 15; Arber, 1905, p. 36, 37). From Brazil similar evidence of seasons was obtained in fossil trees of the same age. (I. C. White, 1908). Physicists have shown, that so far as can be judged from any known evidence, polar wandering, at least to any appreciable extent, has not taken place during the known geological history of the earth. (Barrell, 1914, p. 333–340).

Blackwelder has argued that there are ancient glacial clays without associated tillites. (See *ante*, p. 58). It is probable that many more await discovery. As has been noted in a former paper (Sayles, 1916), the chances for the preservation of clays are much greater than for tills, for the reason that clay is deposited

in water, and till originates largely on the lands above the water level. Unless the lands on which tills are deposited sink relatively soon after the withdrawal of the glaciers which formed them, such tills would be eroded and lost, so far as any geological record of them is concerned. It is impossible to know how much of the till of the Pleistocene period will be preserved as tillite. It is safe to say, however, that unless submergence operates on a large scale, and relatively soon, a very small proportion of the Wisconsin and earlier Pleistocene tills will be preserved as tillites. The chances of the exposure of such problematical Pleistocene tillites would also be small. It is even possible that no tillite at all of the Pleistocene period will be exposed as evidence of that period. The chances of the preservation of the record in Pleistocene clay, however, would be greater, even though the area covered by the Pleistocene glacial clays is much less than the area covered by tills of the same age.

As previously stated many shales and slates with banding occur which have not been investigated, in regard to either glacial origin or seasonal deposition, and until such an investigation is made it will not be possible to say how important the ancient glacial clays will be in the study of ancient climates of the earth. It is probable, however, that Glacial periods of the past, of which we have no clue at present, will be discovered by means of ancient glacial clays, even though no tillites of such periods will ever be found.

8. LITERATURE CITED.

ATWOOD, W. W.

Eocene glacial deposits in southwestern Colorado. Professional paper, 95 B U. S. G. S., 1915.

ARBER, E. A. N.

Catalogue of the Glossopteris flora. London, 1905.

BARRELL, JOSEPH.

The status of hypotheses of polar wanderings. Science, 1914, new ser., **40**, p. 333–340.

[Banded glacial slates]. Bull. Geol. soc. Amer., 1915, **27**, p. 112, 113.

Rhythms and the measurements of geologic time. Bull. Geol. soc. Amer., 1917, **28**, p. 745–904, pl. 43–46.

BERKEY, C. P.

Laminated interglacial clays of Grantsburg, Wis. [with chronological deductions.]. Journ. geol., 1905, **13**, p. 35–44.

BLACKWELDER, ELIOT.

On the probable glacial origin of certain folded slates in southern Alaska. Journ. geol., 1907, **15**, p. 11–14.

See WILLIS, BAILEY, BLACKWELDER, ELIOT, and SARGENT, R. H.

BLANFORD, W. T. and H. F. and THEOBALD, WILLIAM, JUN.

On the geological structure and relations of the Talcheer coal field, in the district of Cuttack. Mem. Geol. surv. India, 1859, **1**, p. 33–88.

BRITTLEBANK, C. C. *See* SWEET, GEORGE and.

COLEMAN, A. P.

The duration of the Toronto interglacial period. Amer. geol., 1902, **29**, p. 71–79.

CORSTORPHINE, G. S. *See* HATCH, F. H. and.

DARWIN, G. H.

The tides. Boston, 1898.

DAVID, T. W. E.

The Permo-Carboniferous glacial beds at Wynyard, near Table Cape, Tasmania. 11th rept. Australasian assoc. adv. sci., 1908, p. 274–279, 1 pl.

DAVID, T. W. E. and PRIESTLEY, R. E.

Geological observations in Antarctica by the British Antarctic expedition 1907–1909. Shackleton's The heart of the Antarctic, 1909, **2**, p. 276–331.

EMERSON, B. K.

The Connecticut Lake of the Champlain period, north of Holyoke. Amer. journ. sci., 1887, ser. 3, **34**, p. 404, 405.

[Interglacial conditions in New England]. Amer. geol., 1893, **11**, p. 174.

Geology of Old Hampshire county, Massachusetts * * * Monog. **29**, U. S. G. S., 1898.

Geology of Massachusetts and Rhode Island. Bull. 597, U. S. G. S., 1917.

FERGUSON, H. G.

Tertiary and Recent glaciation of an Icelandic valley. Journ. geol., 1906, **14**, p. 122–133.

FULLER, M. L.

Season and time elements in sand-plain formation. Journ. geol., 1899, **7**, p. 452–462.

GEER, GERARD DE.

A geochronology of the last 12,000 years. Compte rendus Cong. geol. intern., sess. 11, 1910, 1912, p. 241–253, 2 pls.

HALLE, T. G.
On the geological structure and history of the Falkland Islands. Bull. Geol. inst. Univ. Upsala, 1912, **11**, p. 115–229, pl. 6–10.
HATCH, F. H. and CORSTORPHINE, G. S.
The geology of South Africa. Ed. 2. London, 1909.
HEIM, ALBERT.
Handbuch der gletscherkunde. Stuttgart, 1885.
HITCHCOCK, EDWARD.
Final report on the geology of Massachusetts. 2 vols. Amherst, Northampton, 1841.
HOBBS, W. H.
[Banded glacial sediments]. Bull. Geol. soc. Amer., 1916, **27**, 112.
HOGG, E. G. *See* OFFICER, GRAHAM and.
HOWCHIN, WALTER.
Australian glaciations. Journ. geol., 1912, **20**, p. 193–227.
HUNTINGTON, ELLSWORTH.
The solar hypothesis of climatic changes. Bull. Geol. soc. Amer., 1914, **25**, p. 477–590.
JEFFREY, E. C.
The mode of origin of coal. Journ. geol., 1915, 23, p. 218–230.
KINDLE, E. M.
Small pit and mound structures developed during sedimentation. Geol. mag., 1916, new ser., decade 6, **3**, p. 542–547, pl. 13.
LA FORGE, LAURENCE. *See* SAYLES, R. W. and.
LAHEE, F. H.
Contemporaneous deformation: a criterion for aqueo-glacial sedimentation. Journ. geol., 1914, **22**, p. 786–790.
MARBUT, C. F. *See* SHALER, N. S., WOODWORTH, J. B., and.
MELLOR, E. T.
A contribution to the study of the glacial (Dwyka) conglomerate in the Transvaal. Q. J. G. S., 1905, **61**, p. 679–689.
MOLENGRAAFF, G. A. F.
The glacial origin of the Dwyka conglomerate. Trans. Geol. soc. South Africa, 1898, **4**, p. 103–113, 3 pls.
OFFICER, GRAHAM and HOGG, E. G.
The geology of Coimaidai. Part II. The Silurian and glacial beds. Proc. Royal soc. Victoria, 1898, new ser., **10**, p. 180–196, pl. 8, 9.
PHILLIPS, JOHN.
The Malvern Hills, compared with the Palaeozoic districts of Abberley, Wollhope, May Hill, Tortworth, and Ush. Mem. Geol. surv. Great Britain, 1848, **2**, pt. 1, p. 1–330.
PRIESTLEY, R. E. *See* DAVID, T. W. E., and.
RAMSAY, A. C.
On the occurrence of angular, subangular, polished, and striated fragments and boulders in the Permian breccia of Shropshire, Worcestershire, &c.; and on the probable existence of glaciers and icebergs in the Permian epoch. Q. J. G. S., 1855, **11**, p. 185–205.
REID, H. F.
Glacier Bay and its glaciers. 16th rept. U. S. G. S., 1896, pt. 1, p. 415–461, pl. 86–96.
RINK, H.
Die neuern dänischen untersuchungen in Grönland, 1887. Petermanns mitteil., 1888, **34**, p. 67–74.

ROGERS, A. W.

Geological survey of Bechuanaland and Griqualand West. 11th ann. rept. Geol. comm. South Africa, 1906, p. 43.

SARGENT, R. H. *See* WILLIS, BAILEY, BLACKWELDER, ELIOT, and.

SAYLES, R. W.

The Squantum tillite. Bull. M. C. Z., 1914, **56**, p. 139–176, 12 pls.

Banded glacial slates of Permo-Carboniferous age, showing possible seasonal variations in deposition. Proc. Nat. acad. sci., 1916, **2**, p. 167–170.

SAYLES, R. W. and LA FORGE, LAURENCE.

The glacial origin of the Roxbury conglomerate. Science, 1910, new ser., **32**, p. 723, 724.

SEDERHOLM, J. J.

Sur la géologie quaternaire et la géomorphologie de la Fennoscandia. Bull. 30, Comm. géol. Finlande, 1911, p. 1–66, ills.

Subdivision of the pre-Cambrian of Fenno-Scandia. Compte rendu Cong. géol. intern., sess. 11, 1910, 1912, p. 683–698.

SHALER, N. S.

Origin of the divisions between the layers of stratified rocks. Proc. Boston soc. nat. hist., 1888, **23**, p. 408–419.

SHALER, N. S., WOODWORTH, J. B., and MARBUT, C. F.

The glacial brick clays of Rhode Island and southeastern Massachusetts. 17th rept. U. S. G. S., 1896, pt. 1, p. 951–1004, pls. 61, 62.

SHIRLEY, JOHN.

Additions to the fossil flora of Queensland * * *. Bull. 7 Geol. surv. Queensland, 1898.

STRAHAN, AUBREY.

On glacial phenomena of Palaeozoic age in the Varanger Fiord. Q. J. G. S., 1897, **53**, p. 137–146, pl. 8–10.

SWEET, GEORGE and BRITTLEBANK, C. C.

The glacial deposits of the Bacchus Marsh District. 5th rept. Australasian assoc. adv. sci., 1894, p. 376–389, pl. 12, 13.

TARR, R. S.

The Yakutat Bay region, Alaska. Professional paper 64, U. S. G. S., 1909.

The glaciers and glaciation of Alaska. Science, 1912, new ser., **35**, p. 241–258. Ann. Assoc. Amer. geogr., 1912, **2**, p. 3–24, pl. 1.

TAYLOR, F. B.

The limit of postglacial submergence in the highlands east of Georgian Bay. Amer. geol., 1894, **14**, p. 273–289, pl. 7.

THEOBALD, WILLIAM, JUN. *See* BLANFORD, W. T. and H. F. and.

TYNDALL, JOHN.

Heat considered as a mode of motion. London, 1865.

UPHAM, WARREN.

Sublacustrine till. Amer. geol., 1896, **17**, p. 371–375.

WHITE, I. C.

Report on the coal measures and associated rocks of South Brazil. Comm. estud. Minas Brazil. Rio de Janeiro. 1908.

WILLIS, BAILEY, BLACKWELDER, ELIOT and SARGENT, R. H.

Research in China. Carnegie inst. publ., 54, 1907, **1** pt. 1.

WILSON, M. E.

Kewegama Lake map area, Quebec. Can. geol. surv., 1913, **39**.

WOODWORTH, J. B.

Ancient water levels of the Champlain and Hudson valleys. Bull. 84, N. Y. state mus., 1905.

See SHALER, N. S., WOODWORTH, J. B., and MARBUT, C. F.

WRIGHT, G. F.

The ice age in North America. Third edition. New York. 1891.

Age of the Don River glacial deposits, Toronto, Ontario. Bull. Geol. soc. Amer., 1914, **25**, p. 205–214.

EXPLANATION OF THE PLATES.

PLATE 1.

PLATE 1.

SECTION IN THE LAMARRE CLAY-PIT, WOODSVILLE, N. H.

A description of this section has been given (p. 18). The numbers on the right hand denote the different members of the formation, as given in the text and in Figure 1, p. 18. Numbers 23–30, shown in Figure 1, but not here, were taken from a section of the pit about 100 feet to the left of this locality. Numbers 26–27 may be seen in part in Plate 10, fig. 1.

Members of the section from 1–22 in descending order.

22 Annual layers $\frac{1}{2}$ inch at bottom, $\frac{1}{4}$ inch at top.
21 Contortions with till.
20 Annual layers $\frac{1}{2}$ inch thick.
19 Contorted layers with trace of till.
18 Annual layers $\frac{1}{2}$ inch thick.
17 Contorted layers with till.
16 Annual layers $\frac{1}{2}$ inch thick.
15 Contorted layers with till on top.
14 Annual layers $\frac{1}{2}$ inch thick.
13 Contorted layers with till on top.
12 Annual layers $\frac{1}{2}$ inch thick.
11 Contorted layers with till on top.
10 Annual layers $\frac{1}{2}$ inch thick.
9 Till layer on 8.
8 Contorted layers with till on top.
7 Annual layers $\frac{3}{4}$ inch thick.
6 Gravel layer.
5 Rock-flour.
4 Annual layers $\frac{1}{2}$ inch thick.
3 Rock-flour.
2 Gravel and rock-flour.
1 Annual layers $\frac{1}{4}$ inch thick.

SCALE—ONE QUARTER INCH = 1 FOOT

HELIOTYPE CO. BOSTON

PLATE 2.

PLATE 2.

Figure 1.— Seasonal Banding in Glacial Clay at Woodsville, N. H.

Although it may be a mistake to speak of typical seasonal banding, the specimen here shown gives an idea of the conditions of seasonal deposition in the glacial clays most commonly seen in the clays of the Connecticut Valley and in many other localities. The characters of seasonal banding vary according to the conditions of deposition. For at least 1,500 years the widths and general characters of the bands show remarkable uniformity. This has been discussed on p. 23. On the seasonal hypothesis, the relatively small amount of material in the coarse components of the banding, does not appear to indicate a long hot summer, but rather a short and moderate summer season. The particles of the fine dark component are very small, some of them being not over 1/1000 mm., and the average is about 1/600 mm. The particles of the coarse component average about 1/200 mm., with some as coarse as 1/12 mm. Some of the sediment in this coarse component is as fine as that found in the fine component, but the amount of this fine material is very small.

Figure 2.— Banded Slate from Squantum.

Specimen of glacial slate from just south of the viaduct connecting Squantum with Moon Island. For the purpose of photographing, the dark layers have been slightly darkened to bring out contrast. This specimen was exhibited at the Albany meeting of the Geological Society of America in 1916. The resemblance of this banding to the banding of the clay specimen above, is striking. Note the homogeneous layers of fine material in comparison with the coarser layers of lighter shade. The changes in the conditions of deposition, as shown by the minute stratification in the coarse components, may be compared with the similar stratification in the clay specimen above. There were about eight changes of conditions, on the average, registered in the slate, while in the clay there is an average of about six. Quiet and moving water were responsible for the alternating fine and coarse layers, shown in the coarse components.

6
5
7
7

1

10
8
6
7
8
12
8

2

HELIOTYPE CO. BOSTON

PLATE 3.

PLATE 3.

Figure 1.— Clay and Silt Layers at Lisbon, N. H.

In this figure the banding shows a sudden change of the conditions of deposition near the top. At the bottom the bands are regular in interval and fairly thin. About eight inches from the bottom, at the lower end of the handle of the trowel, there is a sudden appearance of a band about two inches thick with a larger proportion of silt and less clay. This layer is followed by bands having about equal amounts of clay and silt. Then come thinner bands with a very regular interval for two feet. Suddenly, near the top a marked increase in the thickness of the banding can be seen. It is suggested that such a sudden addition of bulk of sediment might be satisfactorily explained by a shifting of the glacial stream nearer to this location.

Figure 2.— Irregular Banding of Clay and Silt at North Bath, N. H.

View taken at a section about 150 feet above the Ammonusuc River. No banding can be found in the Squantum slate with more irregular intervals of deposition than are found here. As has been noted (p. 39), in coarse sediments no regular intervals in the banding need be expected on account of the changing nature of streams coming from a glacier. Only in undisturbed places can undisturbed, regular banding be expected. In this case the sediment is coarser than at Woodsville; the clay has less plasticity and the silt approaches a very fine sand. The sizes of the sediments are about the same as in the average Squantum slate, such as is found in positions near the tillite. The irregularities found here are probably due to shifting and varying streams, from year to year. It does not seem probable that variations in yearly temperature could account for the various thicknesses shown, although as indicated (p. 39) this may be possible.

1

2

HELIOTYPE CO. BOSTON

PLATE 4.

PLATE 4.

Figure 1.— Wide Banding in Clay and fine Sand, two Miles North of Hanover, N. H., on the Vermont Side of the Connecticut River.

Till lies from about fifteen to twenty feet below the section here shown. Above the till comes sand of coarse texture, alternating in no markedly regular manner with finer sand. For about ten feet these alternations can be traced. Then comes an interval of from ten to twelve feet which shows no good exposures. The first clay appears about twenty-five feet above the till in a layer about six inches thick. In the view this layer appears as a dark band at the bottom of the cut made to the left of the little girl. Then come three feet of very fine sand, above which another dark layer of clay appears, about five inches thick. Above this clay layers of fine sand about ten inches thick may be seen, and then another layer of clay about seven inches thick. The next layer of clay may be seen at the extreme upper left hand corner of the plate. From this point upward layers of silt and clay alternate in ever decreasing widths and finally at the top of the deposit the seasonal layers are not over $\frac{3}{4}$ inch thick. The wonderful uniformity of the change from thick to thin bands which this remarkable deposit shows from bottom to top may be explained most satisfactorily, according to present knowledge, by a retreat of the glacier. In this case it would appear that the retreat was relatively rapid. See Plate 5, fig. 1, for the upper part of this exposure.

Figure 2.— Alternating coarse and fine, wide Bands at Squantum Head, Mass.

Lying on the tillite at Squantum Head come transition beds of alternating slate and conglomerate beds which show considerable regularity of interval as compared with the transition beds on the tillite in other places. The conglomerate in the first beds is fairly coarse, containing pebbles with an average diameter of about one inch and these first beds are about one foot thick. Alternating with these conglomerates are layers of slate about four inches thick. About ten feet above these layers, come the bands shown in this view. The hammer near the middle of the picture indicates the scale. The head of the hammer rests on a bed of very fine conglomerate about six inches thick. The shadow of the handle of the hammer covers the overlying layer of slate. Several layers of alternating slate and fine conglomerate may be seen above. From a study of the slate layers here shown (see Plate 6, fig. 2 for a detail view of the slate) it would appear that the winter seasons of this time were not continuously cold, but broken by thaws somewhat as at present. Warmer conditions must have set in, for the glacier was retreating. In this case, the conglomerate layer would mean a short and very warm summer with longer falls and springs than at the present time.

1

2

PLATE 5.

PLATE 5.

Figure 1.— Banding in Clays about two Miles North of Hanover, N. H., on the Vermont Side of the Connecticut River.

This view shows the upper ten feet of the section of which Plate 4, fig. 1 is near the bottom. The annual deposit at the bottom is about six inches thick, while near the top the annual deposit is not over one inch thick. The bands grow thinner very uniformly from bottom to top with no tendency to thickening. From a close study of this deposit it is inferred that the cause of this progressive thinning is due to retreat of the glacier and the consequent diminution in the supply of material as the glacier withdrew. About fifty annual deposits can be counted from the bottom to the top of the bank, which is three feet above the top of the view. This includes about twelve feet. From the comparatively thick annual deposits at the top (about $\frac{3}{4}$ inch) it is believed that much of the original deposit has been eroded. The entire section of sands and banded clays is about fifty feet thick above the till at the bottom. See Plate 4, fig. 1 for a description of the lower part of this section.

Figure 2.— Banded Slate at Squantum about 150 Feet above the Tillite.

Shows regular banding averaging about one inch for the fine and coarse layers. Just below the hammer is a zone of crumpling nine inches thick. Near the lower left corner some small pebbles may be seen mashed into the folded layers. Another zone of crumpling about three inches thick may be seen at the top. A small pebble also shows in this zone. The layers do not show progressive thinning here, simply differences in thickness, probably due to normal variations in seasonal temperatures or precipitation.

1

2

HELIOTYPE CO. BOSTON

PLATE 6.

PLATE 6.

Figure 1.— Intraseasonal Banding in Clay, near Hanover, N. H.

In favorable localities it is possible to study the changes in deposition that took place during individual years. To undertake such a study some locality must be found where there was a maximum of deposition with a minimum of disturbing factors. This view shows such conditions. The exact location of the bands shown may be found by comparing Plate 5, fig. 1. About one foot below the trowel slightly to the left may be seen a light-colored form pointed downward, some dry clay not removed by the trowel in making a fresh surface. The winter layer is nearly covered by the disc and is about one inch thick. The summer layer below is four inches thick. In this summer layer about twenty-one minor changes in deposition may be counted, denoting higher and lower water conditions. Whether these alternating layers mean cooler and warmer conditions, or wet and dry, it is impossible, in any given layer, to say. The winter layers also show differences in deposition in some cases, but as a rule, the clay layers of winter are homogeneous, with no evidence of thaws.

Figure 2.— Alternating Layers in the Slate between Layers of fine Conglomerate, Squantum Head, Mass.

For the general description of this deposit see Plate 4, fig. 2.

1

2

PLATE 7.

PLATE 7.

Figure 1.— CONTORTED BANDS IN CLAY, WOODSVILLE, N. H.

Two specimens are photographed in this figure. On the left there are ten well-shown annual deposits. The three lower bands are horizontal and those above show contortions and faults. In each of the bands there appears a characteristic which is very common in the glacial clays and also in the glacial slate at Squantum. It will be noted that on top of the winter or dark layer of clay is a thin layer of silt which shows in light color. Above this silt layer is a thin layer of clay. Above this comes the much thicker layer of silt denoting summer deposition. This silt gradually becomes finer upward and merges into the next clay or winter deposit. It is inferred that where the thin layer of silt follows the clay the cause may be a breaking up of the ice in the spring with temporary high-water conditions from the melting. This condition may then be followed by another freeze and quiet conditions of deposition for a short time, followed by normal summer conditions as indicated by the thicker layer of silt. It is also possible to interpret the thin silt layer in a different way. If the territory in front of the ice should be devoid of snow, a high wind might easily spread dust or even sand over the winter ice, covering the area of clay deposition. On the melting of such ice in the spring this wind-blown material would settle to the bottom. In this way a layer of coarse material might become intercalated between the fine clays. The peculiar character described above is not always present in the glacial clays but is very common. The remarkable contortions on the right are noteworthy.

Figure 2.— CONTORTED GLACIAL CLAY, WOODSVILLE, N. H.

1

2

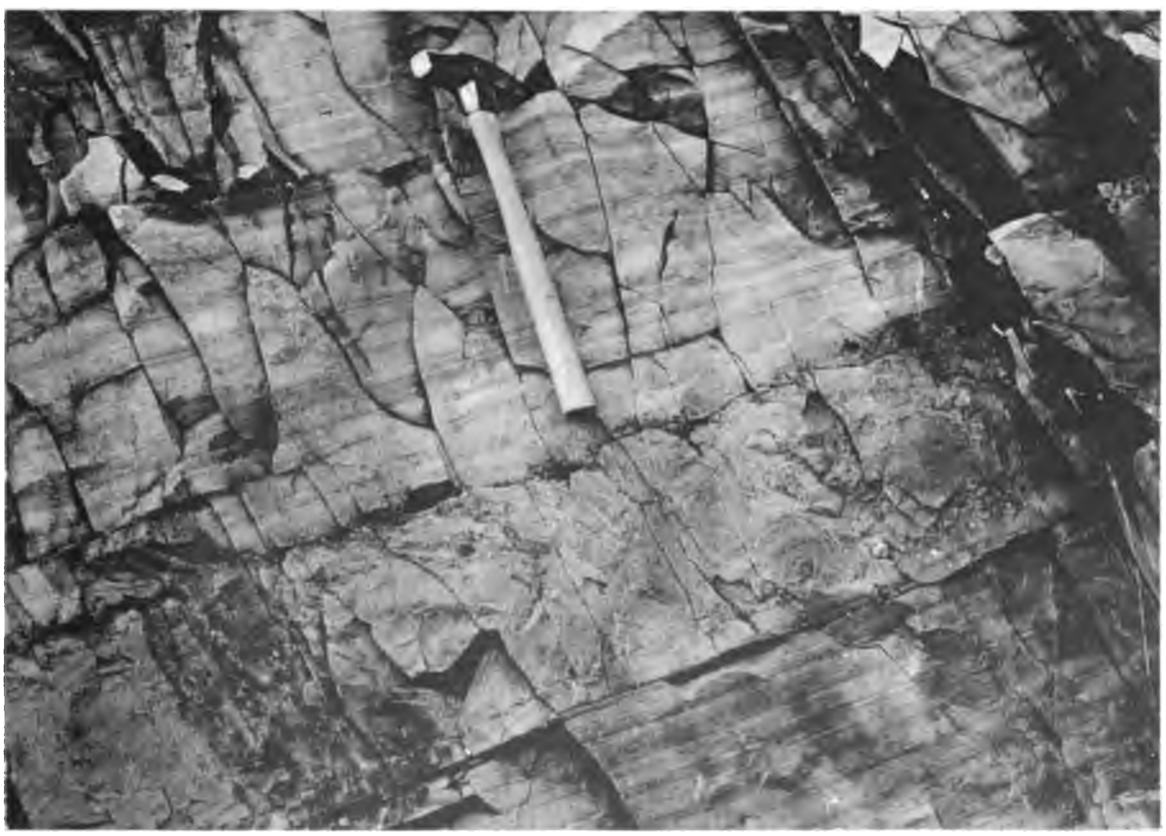
PLATE 8.

PLATE 8.

Figure 1, 2.—CONTORTED BANDS LYING BETWEEN THE UNDISTURBED BANDS BETWEEN NORTH BATH AND LISBON, N. H.

In this Plate a comparison is made between clay and slate in cases where a contorted zone lies between undisturbed layers. The contorted zone in Figure 1 is twelve inches thick and in Figure 2 eleven inches. The banding is of the same nature in both views. The peculiar mashed appearance is also the same in both views. Pebbles may be seen mixed with the contortions in Figure 2, but none were found in the specimen shown in Figure 1, but they may occur. At Woodsville pebbles were found in many contorted zones. These views show typical cases of what are believed to be deformations due to the grounding of bergs. The pebbles must have come from the melting of the ice at the bottom of the bergs, which would often contain rock materials. If the bergs should become inverted in the water on breaking away from the ice front, thus presenting a clean surface on the bottom, neither pebbles nor till would be found in the contorted strata underneath.

1



2

HELIOTYPE CO. BOSTON

PLATE 9.

PLATE 9.

Figure 1.— Contortions in Clay, Woodsville, N. H.

This figure illustrates one of the thin contorted zones in the clays. Where the trowel passed over the surface in preparing the specimen for the camera, a few trowel marks may be seen which should not be confused with the bedding. Whether ice actually came in contact with some of these thin contorted zones it is not possible to determine. By an over-riding of the ice higher up a shearing action might be initiated along layers lower down, and in this way these thin contorted zones may have been produced. The presence of rock-fragments in a contorted zone would, without doubt, mean ice contact. In this case and in some other cases, both in the clays and in the slates, no rock-fragments have been found. This does not prove that ice did not actually touch the clay, inasmuch as the clean ice of an inverted berg would have no rock material. If the upper contact of the contorted zone is even, with no evidence of violence, the contortions observed might have been the result of shearing.

Figure 2.— Banded Slate showing two contorted Zones, Squantum Head, Mass.

This is a typical view of the banded slate. About five inches above the hammer head, the first contorted zone may be seen. About three inches above this zone, another contorted zone may be seen with no bands apparent. These thin zones of contortions in the slate are of the same nature as similar zones in the clays and must have been produced in the same way or ways. In the clay at Woodsville there are many contorted zones the same as at Squantum in the slate.

1

2

HELIOTYPE CO. BOSTON

PLATE 10.

PLATE 10.

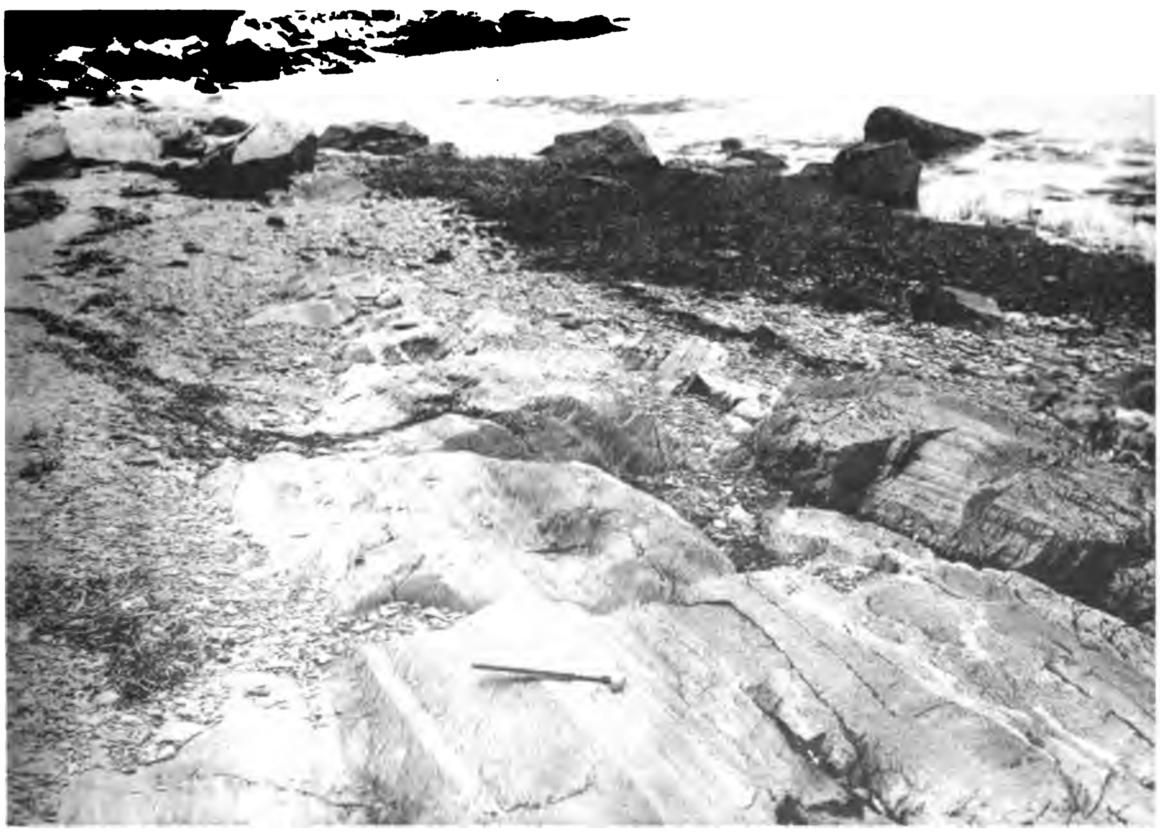
Figure 1. — A TRUNCATED FOLD BENEATH ROCK-FLOUR AND ANNUAL LAYERS, WOODSVILLE, N. H.

This figure illustrates the upper part of member 26, and the lower and middle part of member 27 of the Lamarre clay-pit, described in the text and shown in Figure 1, (p. 18) and Plate 1. Just above the knife may be seen the upper part of a cut-off fold. Above this deformation comes a layer of rock-flour about ten inches thick. A glaciated rock-fragment was found in this rock-flour. Lying on the rock-flour layer are annual deposits about two inches thick for each couple. These couples grow thinner upward and near the top of No. 27 are about one half inch thick.

Figure 2.— TRANSITION BEDS BETWEEN TILLITE AND SLATE FORMATION, SQUANTUM, MASS.

This view shows the irregular nature of the beds lying on the tillite and below the main slate formation at the southeastern end of the Squantum Peninsula. At the right of the centre of the picture the slate begins to show regular banding. This view was taken looking northeast, almost along the strike. The dip here is about 70° S. E.

1



2

HELIOTYPE CO. BOSTON

PLATE 11.

PLATE 11.

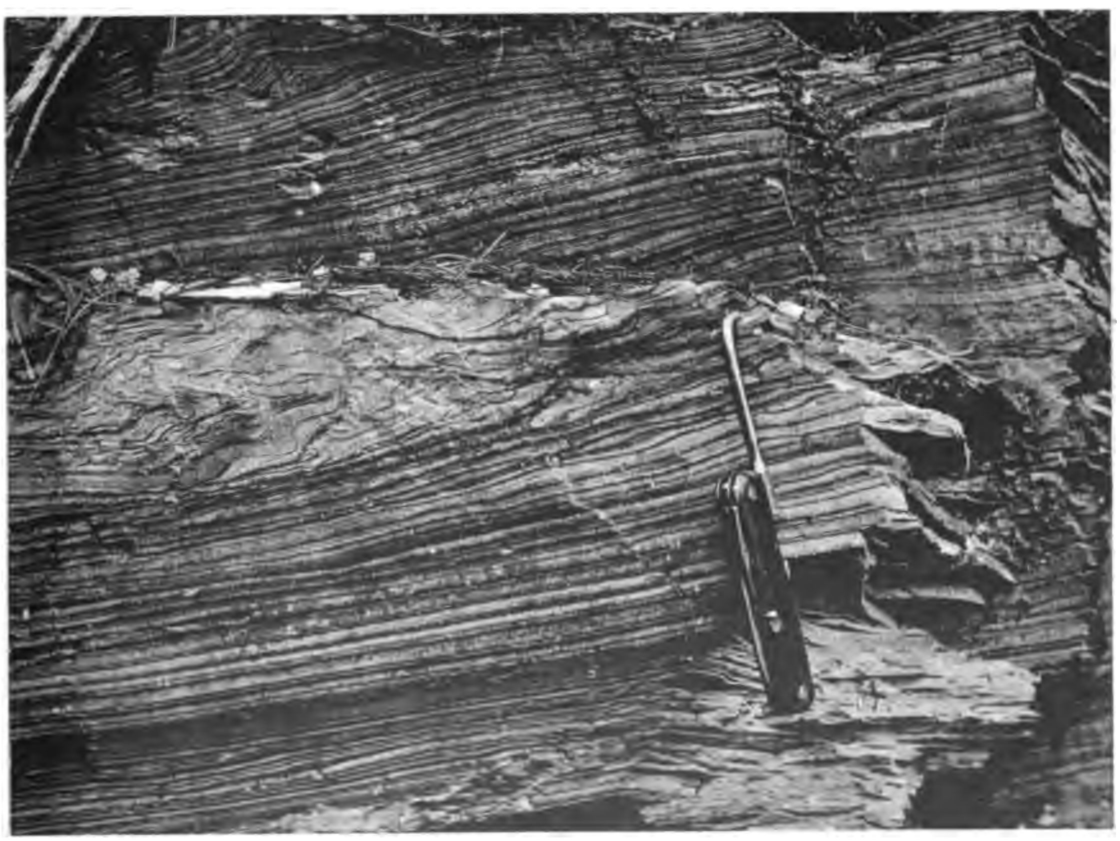
Figure 1.— BANDED CLAY, WOODSVILLE, N. H.

This view is part of that shown in Plate 1. It is shown here for comparison with the slate below.

Figure 2.— LAMINATED SLATE, NEWTON CENTRE, MASS.

The contortions shown are of uncertain origin. There are no pebbles among the layers. It is probable that the result was effected by shearing when the sediments were in an unconsolidated condition. Whether the force which brought on the shearing was over-riding ice above, or was done during later diastrophic movements, it is difficult to say. Tillite does not immediately overlie this slate at Newton Centre.

1



2

HELIOTYPE CO. BOSTON

PLATE 12.

PLATE 12.

Figure 1.— TILLITE BED IN SLATE, SQUANTUM HEAD.

About fifty feet above the tillite at Squantum Head, a bed of tillite occurs intercalated in the slate. At a point one and one fourth inches above the lower right hand corner contact of this tillite with the banded slate is shown and one and one half inches above the lower left hand corner the upper contact. The average thickness of this bed is about four feet. The upper surface of the tillite is uneven as might be expected, and the lower surface, as far as visible, is somewhat uneven also. A large mass of slate is shown on the right. This slate mass was evidently ploughed out of its bed by advancing ice and included in the tillite. Other slate masses of smaller size may be seen to the left of the large fragment. Glaciated pebbles are visible, all through the tillite mass. Two of fair size are near the head of the hammer. The banding above and below the tillite has about the same interval between the bands. It is inferred from this that the water in front of the ice was of about the same depth before and after the advance, and that no glacial stream was very near this particular locality at the time. Further, it is inferred that this advance registers a small oscillation of the ice front and not an advance after an interglacial episode. Another similar bed of tillite, about twenty feet above the tillite and several beds of conglomerate, give evidence of the slow retreat of the main ice sheet. Just as the evidence at Woodsville, N. H. in the glacial clays, points to a very slow, lingering retreat of the Pleistocene ice, so these deposits at Squantum point to a similar slow retreat, marked by many oscillations of the ice front covering many years.

Figure 2.— FOLDED SLATE BETWEEN UNDISTURBED LAYERS, SQUANTUM SOUTHEAST.

About thirty feet above the tillite at Squantum Southeast, in bands of sandstone and slate, these beautifully folded layers occur. The folds are almost vertical but tilted slightly to the west. No pebbles have been observed in the folded zone. There is no cutting off of the folds on top, nor mashing as may be seen in the contorted zones at Squantum Head. As far as can be judged, by the evidence which this very limited exposure presents, the ice did not actually come in contact with the layers. The result observed is probably due to shearing, either by over-riding ice above this horizon, or by diastrophic movements while the beds were unconsolidated. It is also possible that creeping of the beds, induced by heavy superincumbent deposits, may have effected the result.

A

B

1

2

PLATE 13.

PLATE 13.

Figure 1.— BANDED SLATE AT SQUANTUM SOUTHEAST.

At the most southeasterly exposure of the slate at Squantum regular banding commences about thirty feet above the tillite. The first regular bands have about equal amounts of sandstone and slate. The exposure shown here is about 100 feet above the tillite. The sandstone layers have thinned down greatly at this point. The regularity of interval is very marked.

Figure 2.— REGULAR BANDS OF SANDSTONE AND SLATE, SQUANTUM SOUTHEAST.

This figure shows regular banding. The specimen was collected from a horizon about twenty feet lower down in the formation than the slate shown in Figure 1. The sandstone layers are slightly thicker than in the above view, and much thinner than in the bands first showing regularity of interval about thirty feet above the tillite.

1

2

HELIOTYPE CO. BOSTON

PLATE 14.

PLATE 14.

Figure 1.— Fine Banding in Clay, Woodsville, N. H.

The specimen figured was taken about fifteen feet below the top of the highest clay deposit at the Lemarre clay-pit. Just above this horizon these fine bands are contorted and cut off on top. A glacial pebble was taken from the mass lying on this contorted zone. The bands above the disturbed part are at least two inches thick, but within five feet they are not over one half inch thick, and at the top of the deposit are fully as thin as the bands shown in this figure. Such evidence would appear to point to an advance of a thin ice tongue, which destroyed many layers, as evidenced by the contorted and cut-off zone, and then a retreat, steady and rapid, which closed the glacial episode in the vicinity of Woodsville. The bands shown are the thinnest found in the Woodsville locality.

Figure 2.— Fine Banding in Slate taken from Pleistocene Drift, Newton Centre, Mass.

The banding of this specimen is much like that shown in the Woodsville clay, Figure 1, and also much like the fine banding at Squantum.

1

2

HELIOTYPE CO. BOSTON

PLATE 15.

PLATE 15.

Figure 1.— BANDED CLAY, WOODSVILLE, N. H.

The specimen figured shows the difference in thickness between the layers of banded clay. The regularity of interval is what might be called "average" for banded clay. The thickness of the summer layer is more variable, as a rule, than the winter layer. The summer layers show in light color. It may be seen that these light layers vary between 1/32 of an inch to as much as ½ of an inch. Where the summer layers are very thin, the winter layers also show thinning.

Figure 2.— THE FINEST BANDED SLATE AT SQUANTUM.

This finest slate occurs at the highest observable outcrop of slate at the Squantum Head locality, about 800 feet above the tillite. Chlorite is the predominant mineral in its composition, giving a light green tint. It is most probable that erosion of a melaphyre area is responsible for the material of this finest banded rock in the glacial series of Squantum.

Figure 3.— BANDED SLATE, SQUANTUM HEAD.

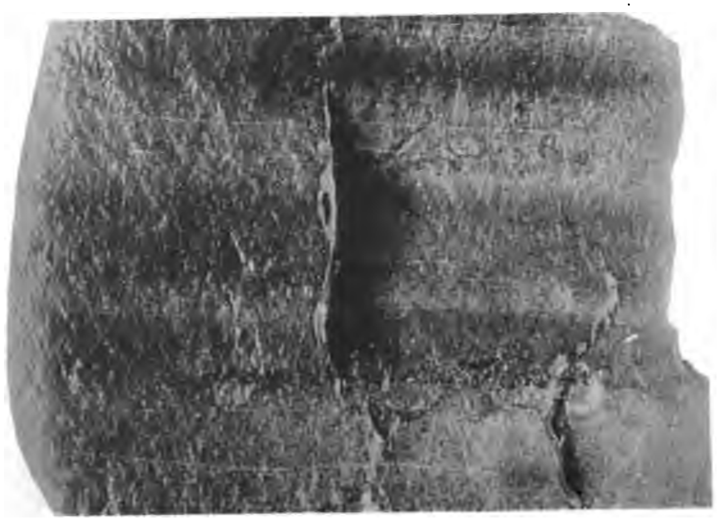
The light layers are of coarse material and the dark, fine. The regularity of interval is marked. The irregularities are no greater than in the specimen of banded clay shown in Figure 1. Note the fine lines in the coarse similar to those seen in Plate 16.

Figure 4.— BANDED SLATE, SQUANTUM HEAD.

Weathering has not acted to the same extent on this specimen as on the one shown in Figure 3. The clearness with which banding shows in much of the slate without sandstone layers is due to weathering.

1

2



3

4

HELIOTYPE CO. BOSTON

PLATE 16.

PLATE 16.

Figure 1.— Photomicrograph of Squantum Tillite.

The following minerals have been found in the tillite:—quartz, feldspar, sericite, epidote, melaphyre, chlorite, limonite, quartzite, and calcite. The angular rock particles of the matrix vary in size from coarse sand down to those with a diameter of 1/1000 mm. or less.

Figure 2.— Photomicrograph of Banded Slate, Squantum Head.

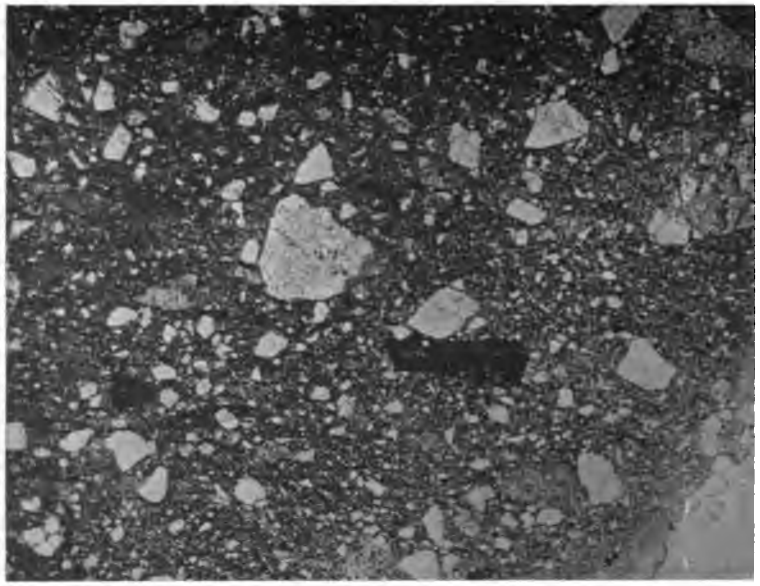
This shows a typical specimen of the banding above the tillite at Squantum Head. These layers were chosen so that the complete cycle could be easily shown in one view. The magnification here is ten diameters. It will be noted that the layer of fine material is on the whole, homogeneous in its nature. The transition from coarse to fine upward is usually gradual, as in Figure 3, Plate 16. The transition from fine to coarse is usually abrupt, and the finest material of the fine layer is on top. This finest material on top is often beautifully rippled by extremely gentle current action. It sometimes happens that this finest material on the fine layer is absent. In such cases it is most likely that the succeeding currents of the active water phase of the cycle have removed it. In the layer of the active water phase tiny lenses of very fine material may be seen. From a study of many slides in which continuous threads of such fine material are present, it is inferred that these lenses are merely remnants of such fine layers.

Figure 3.— Photomicrograph of coarse Layer.

This is a view of the coarse layer seen in Figure 2. It was taken near the top of the coarse layer and shows the transition between the coarse and the fine layers. The magnification here is about twenty diameters. Note how gradual the transition is compared with the abrupt change from fine to coarse. Note also the disturbed nature of the material as compared with the undisturbed nature of the fine.

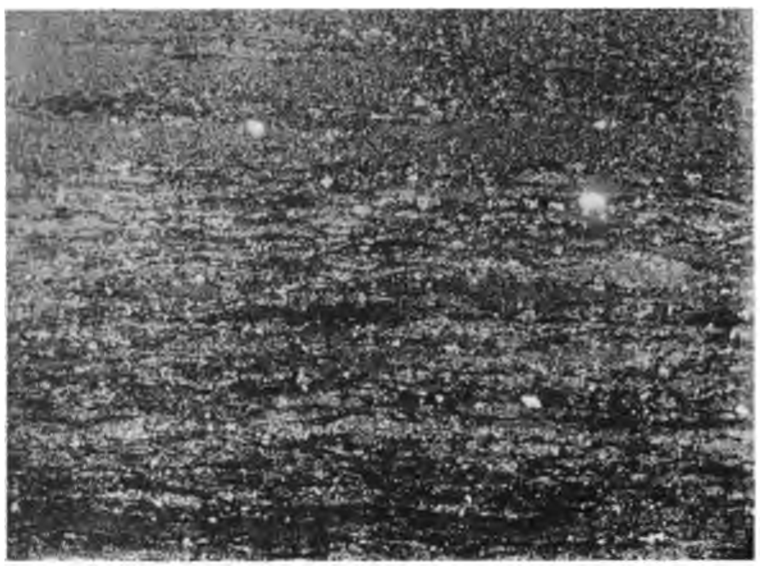
Figure 4.— Photomicrograph of fine and coarse Layers.

This shows the fine and coarse of another specimen. Only part of each layer shows. The magnification is about ten diameters as in No. 2. Note the fine sediment at the top of the fine layer. Very gentle ripple-marks may be seen along this horizon. The coarse layer shows extremely thin laminae with very regular intervals. These differences suggest day and night changes, but at present it is only possible to state that there is a difference between glacial streams at night and during the day, and if the conditions of deposition were just right for their registration, such differences in sedimentation should be registered and, at least partially, preserved.

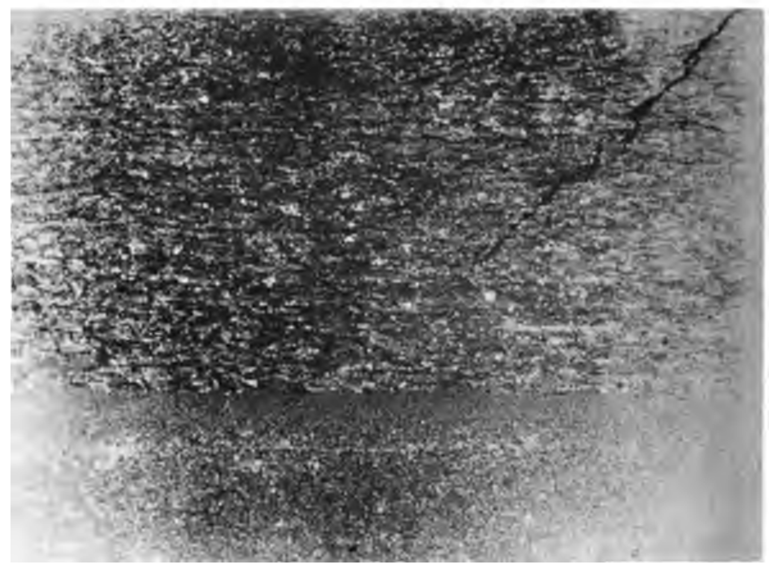


1

2



3



4

HELIOTYPE CO. BOSTON

Date Due

Robert W. Sayles

AUTHOR

Seasonal Deposition in Aqueo-

TITLE

glacial Sediments.

DATE DUE	BORROWER'S NAME	ROOM NUMBER